ANNUAL REPORT

1988

U. S. WATER CONSERVATION LABORATORY
U. S. Department of Agriculture
Agricultural Research Service
Western Region
4331 East Broadway Road
Phoenix, Arizona 85040

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PERSONNEL

The laboratory staff is as follows:

Permanent Employees

Alexander, William L.	Agronomist
Allen, Stephen G.	Research Plant Physiologist
Arterberry, Carl A.	Agricultural Research Technician
Auer, Gladys C.	Physical Science Technician
Bell, Frieda L.	Secretary
Bouwer, Herman	Research Hydraulic Engineer, Research Leader, and Laboratory Director
Bucks, Dale A.	Soil Scientist
Clarke, Thomas R.	Physical Science Technician
Clemmens, Albert J.	Research Hydraulic Engineer
Craft, Mike R.	Physical Science Aide
Davis, Sonya G.	Engineering Draftsman
Dedrick, Allen R.	Agricultural Engineer
Dierig, David A.	Research Geneticist (Plants)
Fink, Dwayne H.	Soil Scientist
Gerard, Robert J.	Laboratory Support Worker
Harner, Paulina A.	Secretary
Hunsaker, Douglas J.	Agricultural Engineer
Idso, Sherwood B.	Research Physicist
Jackson, Ray D.	Research Physicist
Jaynes, Dan B.	Soil Scientist
Johnson, Earl J.	Agricultural Research Technician (Plants)
Johnson, Stephanie	Biological Technician
Kimball, Bruce A.	Soil Scientist
Lewis, Clarence L.	Machinist
McGuire, Cathy	Biological Technician
Martinez, Juan M. R.	Hydrological Technician
Mastin, Harold L.	Computer Assistant
Mills, Terry A.	Computer Programmer Analyst
Moran, M. Susan	Physical Scientist
Benita L. Murphy	Secretary
Nakayama, Francis S.	Research Chemist and Research Leader
Padilla, John	Engineering Technician
Palmer, Joel D.	Agricultural Engineer
Peresta, Gary J.	Physical Science Technician
Pettit, Dean E.	Electronics Engineer
Pinter, Paul J., Jr.	Research Biologist
Rasnick, Barbara A.	Physical Science Technician
Reginato, Robert J.	Soil Scientist and Research Leader
Replogle, John A.	Research Hydraulic Engineer and Research Leader
Rice, Robert C.	Agricultural Engineer
Rish, Shirley A.	Secretary
Seay, L. Susan	Publications Clerk
Seay, Ronald S.	Agricultural Research Technician
Thompson, Anson E.	Research Plant Geneticist
Woomer, E. Elizabeth	Secretary

Temporary Employees

Anderson, Jeff J.	Engineering Technician
Cho, Hyung-Yul	Soil Scientist
Cioto, Elizabeth	Biological Aide
Clyma, Wayne	Agricultural Engineer
Coble, Carrie	Biological Aide
Craft, Michael R.	Physical Science Aide
Giunta, Carol S.	Biological Aide
Harris, Steven M.	Biological Aide
Holtz, Elaine	Physical Science Aide
Klosterman, Evelyn	Biological Aide
Laird, Lisa	Physical Science Aide
LaMorte, Robert L.	Computer Clerk
Lukacsko, Timothy P.	Biological Aide
Merten, Gretchen M.	Biological Aide
Moore, Laurence	Biological Aide
Patterson, Ken A.	Engineering Aide
Perschbacher, Marcella	Biological Aide
Rice, Chalice	Biological Aide
Ronis, Daniel H.	Research Geneticist
Schilreff, Susan	Biological Aide
Souther, Cindy	Physical Science Aide
Strand, Robert J.	Engineering Aide
Vady, Lynn	Biological Technician (resigned 2/88)
West, Jeffrey M.	Biological Aide

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TITLE: CARBON DIOXIDE AND CLIMATE EFFECTS ON PHOTOSYNTHESIS OF SORGHUM

SPC: 1.3.01.1.b 50%
1.1.03.1.d 50%

CRIS WORK UNIT: 5344-11130-001

INTRODUCTION

Interest in the "greenhouse effect", the increase in global surface air temperature induced by a rising atmospheric CO_2 concentration, is rapidly accelerating in the scientific community as well as the general public. If the atmospheric CO_2 concentration doubles during the middle of the next century, as predicted, from the current level of 340 μmol CO_2 mol air^{-1}, most climate modellers believe that global surface air temperatures will rise 1.5 to 4.5 °C (Carbon Dioxide Assessment Committee, 1983).

Many of the climate modellers concede, however, that these estimates ar inconclusive, and that their models exclude the effects of a number of important factors. One of those factors is the response of plants to the predicted climate changes, particularly the increase in CO_2, and how, through a feedback mechanism, the CO_2-induced changes in plant growth will, in turn, affect the climate.

Many controlled environment, ie. laboratory and growth chamber, experiments have shown that increasing atmospheric CO_2 causes an increase in net photosynthesis (Pn) of C3 plants and, to a lesser degree, C4 plants also. In an extensive review of the subject, Cure (1985) concluded that Pn of C3 plants would increase by approximately 28% from a doubling of atmospheric CO_2, whereas Pn of C4 plants would increase by only 5%. Stomatal conductance of water vapor (Gs) decreased by 32 and 35%, respectively, for C3 and C4 crop species from a doubling of atmospheric CO_2.

Less is known, however, about how the atmospheric CO_2 concentration interacts with other climate variables, such as short-wave solar radiation intensity and air temperature, to affect Pn and Gs, particularly as these interactions occur in natural environmental settings. Growth responses of numerous crops have indicated that a positive interaction occurs with increasing temperature; that is, the relative effects of higher atmospheric CO_2 increase as temperature increases (Idso et al., 1987). Allen et al. (1988, 1989) have shown that CO_2 concentration interacts at least as strongly with solar radiation as it does with air temperature to affect Pn of two C3 plants, *Azolla pinnata* and water lily (*Nymphaea marliac*).

The objective of the present experiment was to identify the interactive effects of CO_2 concentration and other environmental variables on Pn and Gs of the C4 species *Sorghum bicolor*, L. Moench; and do so in a semi-natural outdoor environment.

MATERIAL AND METHODS

Hybrid grain sorghum (experimental line RS 610) were started from seed on 1 March 1988. Five seeds were planted in a peat and vermiculite mix (3:1)

in each of 16 11.4-l pots and thinned to 2 seedling per pot 2 weeks lat(The plants were kept in a greenhouse for 30 days, then transferred to f(out-door, open-topped CO_2 enrichment chambers, four pots per chamber. chambers were 2.6 m wide by 5.3 m long with 2 m high clear plastic wal Two of the chambers were continuously supplied with approximately 640 μ CO_2 mol air^{-1} while the other two represented ambient CO_2 conditions about 340 μmol CO_2 mol air^{-1} using the CO_2 distribution system descril by Kimball et al. (1983).

Each pot received 58 g of 14-14-14 slow-release fertilizer on 1 March 1 April. Once in the out-door chambers, the pots were watered three ti per week with distilled water.

Pn, Gs, and leaf minus air temperature (Tl-Ta) were measured hou between 0700 and 1700 hr MST on 26 April, and 3 and 4 May 1988 usin LiCor 6200 portable photosynthesis measurement system. The measureme were made on the first or second leaf from the top of a single plant each pot in each chamber. Short wave solar radiation was measured in adjacent field with an Eppley pyranometer. Air temperature was measu inside of each chamber at a height of 1 m.

The experimental design consisted of two randomized blocks in which f(subsample measurement were taken. Subsample averages were used in statistical analyses.

RESULTS

Hourly average air temperature and short-wave solar radiation measureme for 26 April, and 3 and 4 May are shown in Figure 1. The air temperatu taken at the time of the physiological measurements ranged from about to 36 °C, with only a small difference in the temperature patterns am the three days. Short-wave solar radition ranged from approximately 1 to 1150 W m^{-2}, with nearly identical diurnal patterns for all three da

The diurnal Pn results are presented in Figure 2. Only small differen in Pn between the two CO_2 treatments occurred on 26 April and 3 M although plants in the elevated CO_2 treatment had consistently higher rates, 11.0% averaged over all three days, than those in the ambient C treatment. On May 4, the difference between the two CO_2 treatments w greater, 15.0% when averaged over the entire day. The higher tempe atures on this day may have contributed to the treatment differences providing a more optimal environment for Pn, which, as previously sho for C3 plants (Allen et al., 1988 and 1989), promotes the expression elevated CO_2 effects on Pn. However, this observed response was not lar enough to result in a significant CO_2 by environment interaction, as wi be demonstrated later.

The CO_2 treatment-induced differences in Pn (10.1% averaged over all thr days) are considerably less than those found for Azolla (27.9%) and wat lily (32.4%) grown in ambient and 640 μmol CO_2 mol air^{-1}. Th discrepancy can be attributed to sorghum's more efficient C4 carb fixation mechanism which acts to concentrate CO_2 in the bundle shea

cells of the leaves, thus reducing photorespiration. Increasing the external CO_2 concentration above ambient is, therefore, marginally less effective for the inherently more efficient C4 plants.

Over the entire range of environments experienced in this experiment, the relative difference in Pn between the two CO_2 treatments changed very little. This is apparent in Figure 3, where the slope of the regression of the high CO_2 treatment onto the ambient CO_2 treatment is not different from 1.0 ($P < 0.05$), indicating the lack of a significant CO_2 concentration by environment interaction effect on sorghum Pn. The same regressions for Azolla and water lily are shown in Figures 4 and 5, respectively. For both of these C3 plants, the slopes are significantly greater than 1.0 ($P < 0.05$), implying a significant CO_2 by environment interaction effect on Pn. For these C3 species, the relative difference in Pn between the two CO_2 treatments becomes greater, up to a maximum of about 70%, as the environment becomes generally for favorable for Pn.

Unlike Pn, Gs of sorghum varied greatly between the two CO_2 treatments on all three days. Averaged over all three days, the plants in the 640 μmol CO_2 mol air^{-1} treatment exhibited 27% lower Gs rates than those in the ambient CO_2 treatment (Figure 6). There was also a significant CO_2 by environment interaction effect on Gs. As can be seen in Figures 6 and 7, under conditions that resulted in generally lower Gs rates there was little difference in Gs between the two CO_2 treatments. However, as environmental conditions tended to promote higher Gs rates, the relative difference in Gs between the two treatments increased.

The diurnal Tl-Ta patterns are shown in Figure 8. The ambient CO_2 treatment produced consistently lower Tl-Ta values that the elevated CO_2 treatment. This result is consistent with the higher Gs rates in the ambient treatment. During the early afternoon, the greater transpirational cooling of the leaves in the ambient treatment resulted in leaf temperatures approximately 1.0 to 1.5 °C cooler than air temperature. Leaf temperatures in the high CO_2 treatment declined only to about air temperature, but not below, indicative of lower transpiration and Gs rates.

DISCUSSION

This experiment suggests that substantial savings of water can be expected by C4 plants if the atmospheric CO_2 concentration continues to rise as predicted. These water savings, when combined with the slight CO_2-induced increase in Pn, imply a substantial increase in water use efficiency can also be expected.

The CO_2-induced leaf warming could possibly pose a problem in the future if air temperatures also rise due to the "greenhouse effect". In areas where high temperatures presently affect marginal production, the combination of 1.5 to 4.5 °C air temperatures plus a CO_2-induced 1.0 to 1.5 °C increase in leaf temperature could cause a negative impact on production potential. Fortunately, most C4 crops are relatively tolerant of high

temperatures. Consequently, a CO_2-induced leaf warming may provide the an advantage in cooler climates that are presently suboptimal.

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KIMBALL, B. A., MAUNEY, J. R., GUINN, G., NAKAYAMA, F. S., PINTER, JR. P. J., CLAWSON, K. L., REGINATO, R. J., and IDSO, S. B. 1983. Effects c increasing atmospheric CO_2 on yield and water use of crops. Response c vegetation to carbon dioxide, Series 21, U.S. Department of Energ; Washington, DC. pp. 37.

PERSONNEL: S. G. Allen, S. B. Idso, B. A. Kimball, S. M. Johnson, and G. J. Peresta.

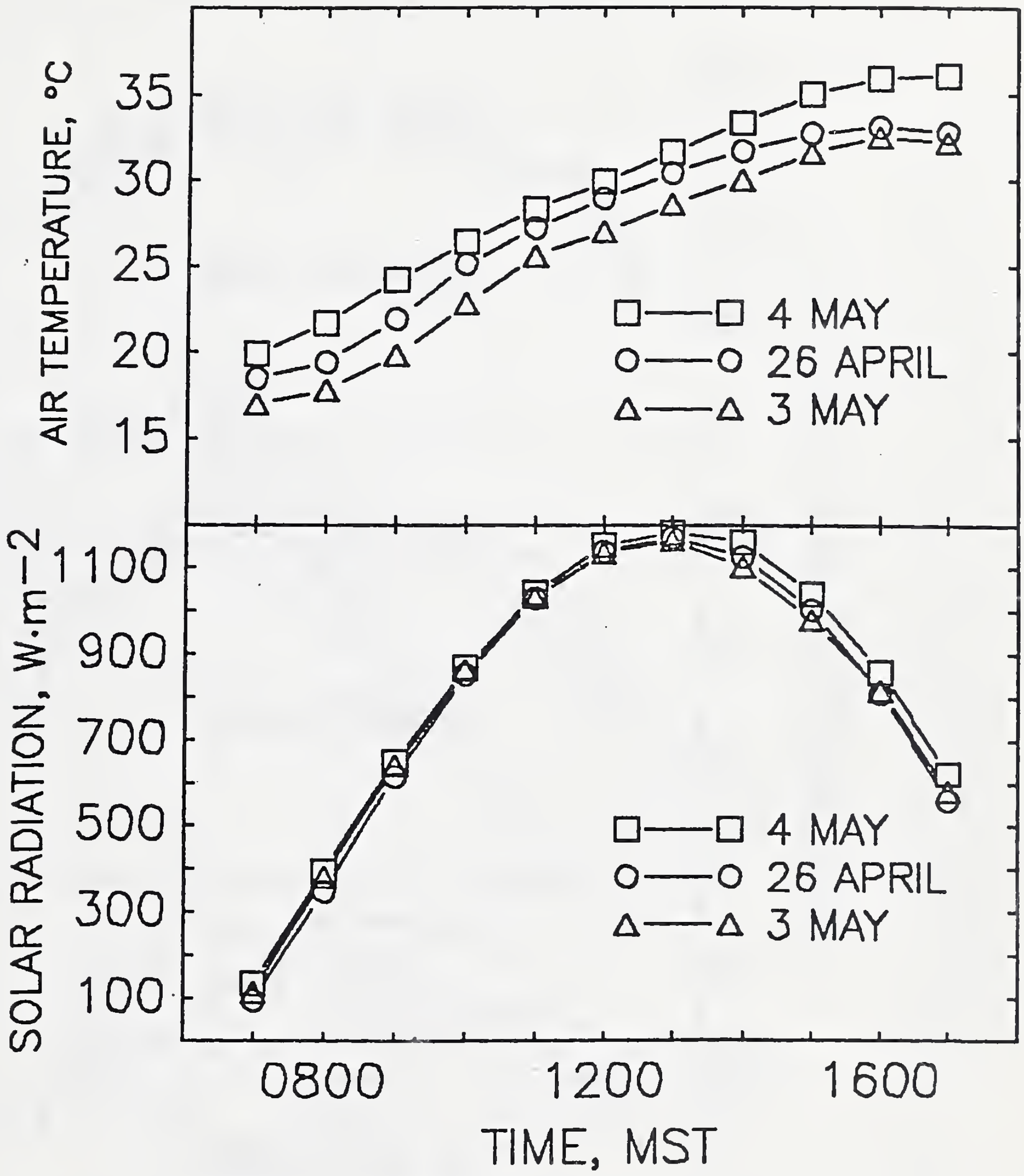

Fig. 1. Air temperature and short-wave solar radiation between 0700 and 1700 hr on 26 April, and 3 and 4 May 1988.

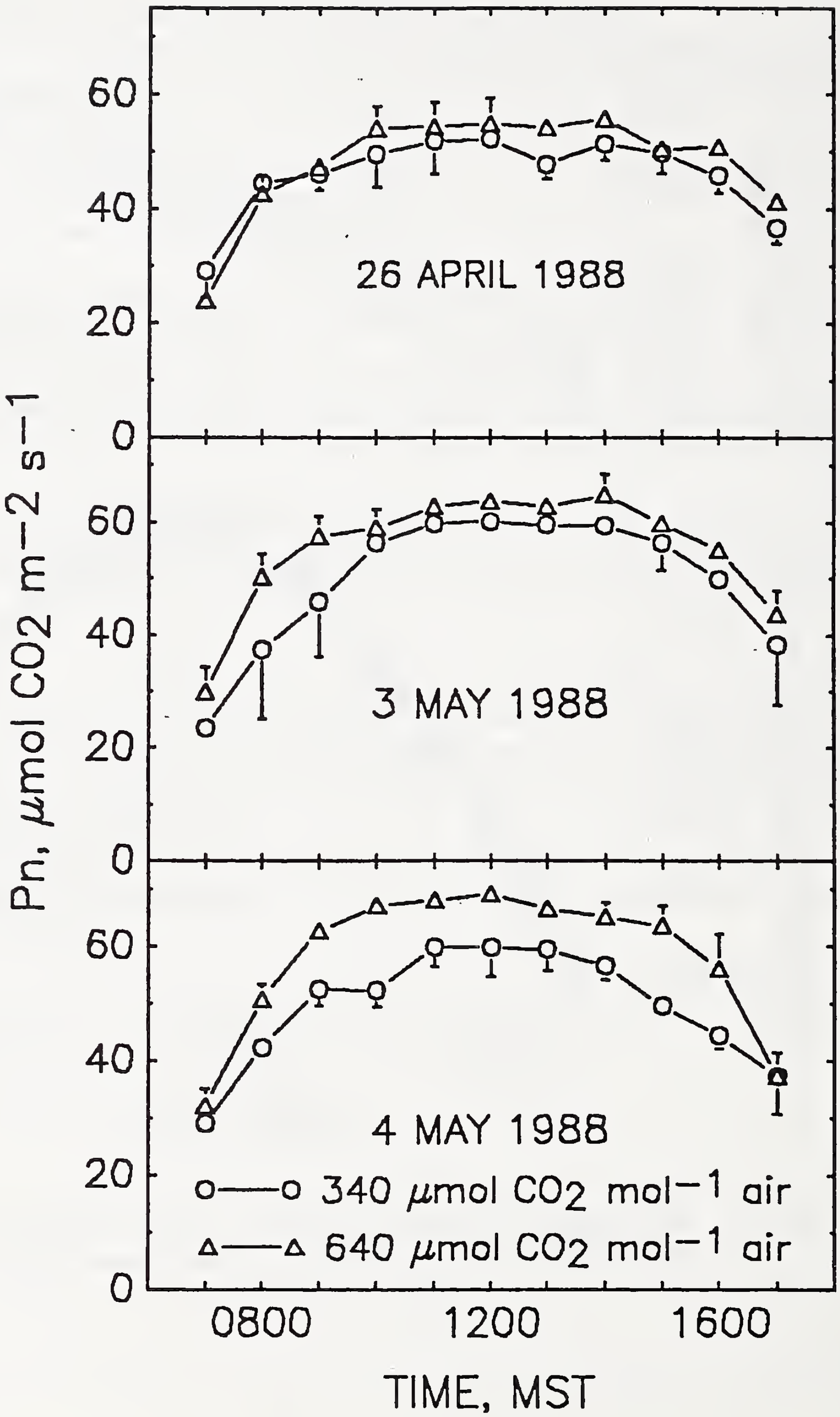

Fig. 2. Net photosynthesis (Pn) of single sorghum leaves in ambient CO_2 and 640 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 4 May 1988. Bars represent standard deviation.

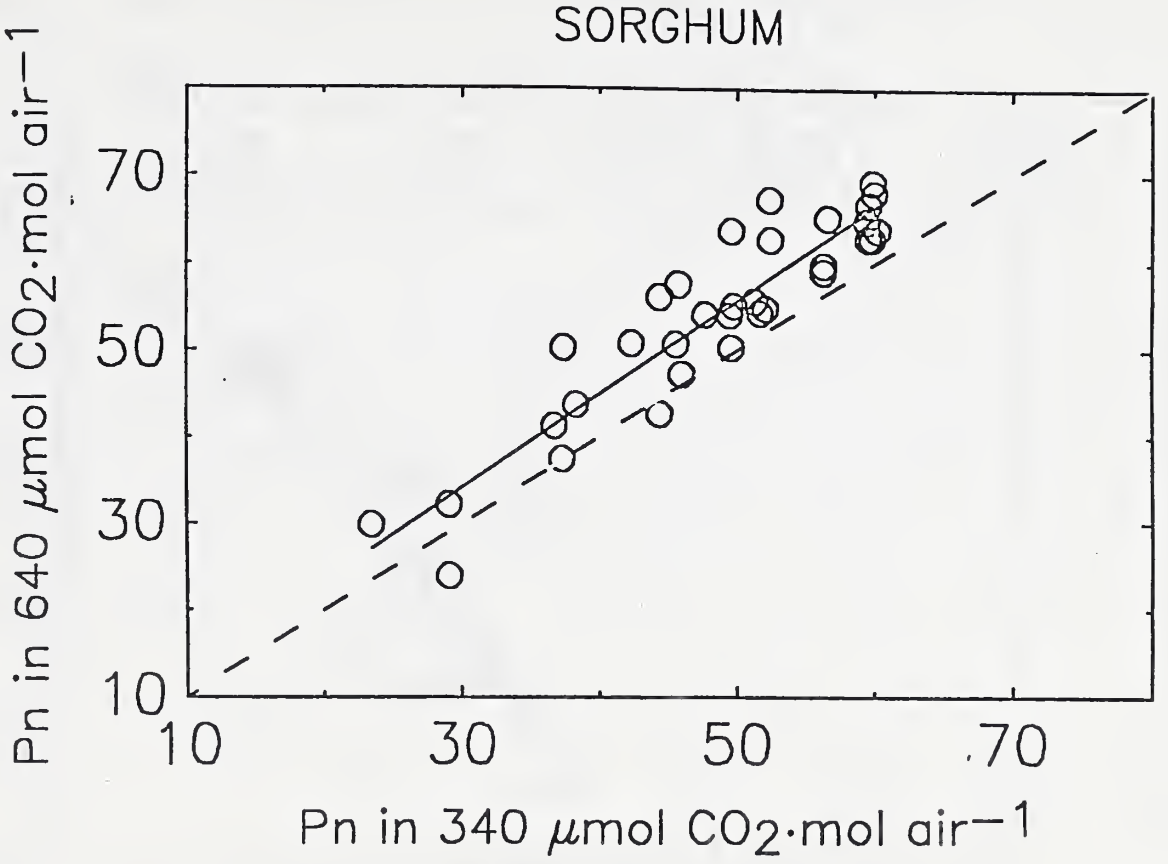

Fig. 3. Linear regression of net photosynthesis (Pn) of sorghum in 640 versus 340 μmol CO_2 mol air^{-1}. n = 33; slope =1.08, not significantly different from 1.00 at $P < 0.05$.

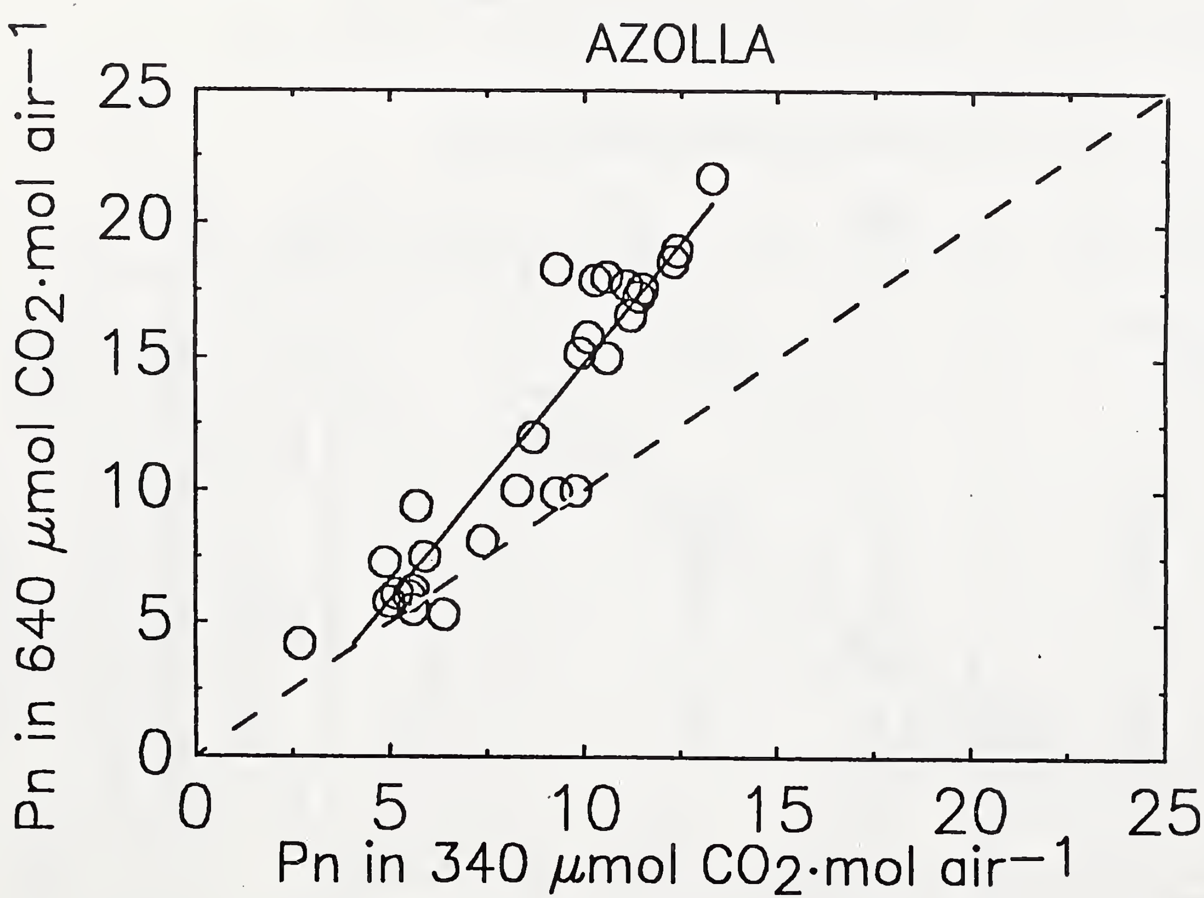

Fig. 4. Linear regression of net photosynthesis (Pn) of <u>Azolla</u> in 640 versus 340μmol CO_2 mol air^{-1}. n = 29; slope =1.80, significantly different from 1.00 at $P < 0.05$. From Allen et al., 1988.

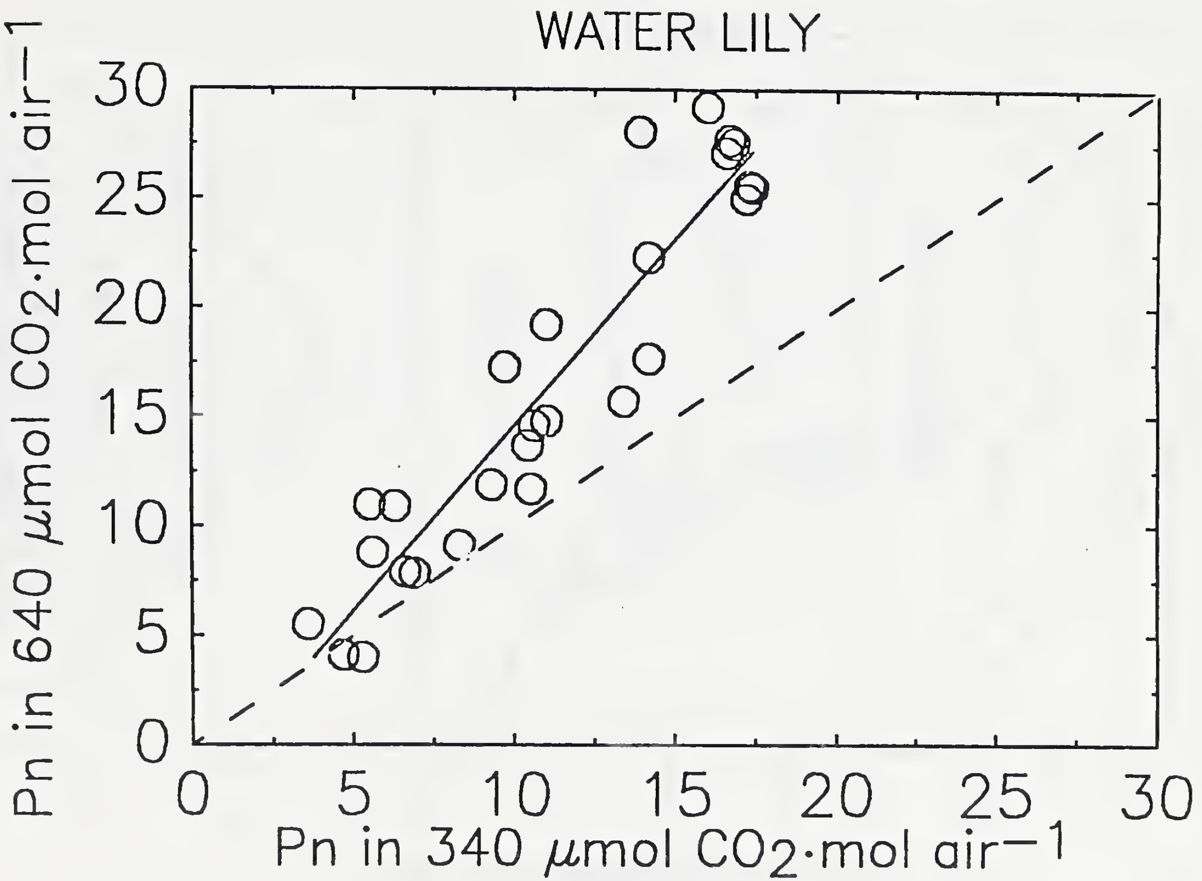

Fig. 5. Linear regression of net photosynthesis (Pn) of water lily in 640 versus 340μmol CO_2 mol air^{-1}. n = 27; slope =1.70, significantly different from 1.00 at $P < 0.05$. From Allen et al., 1989.

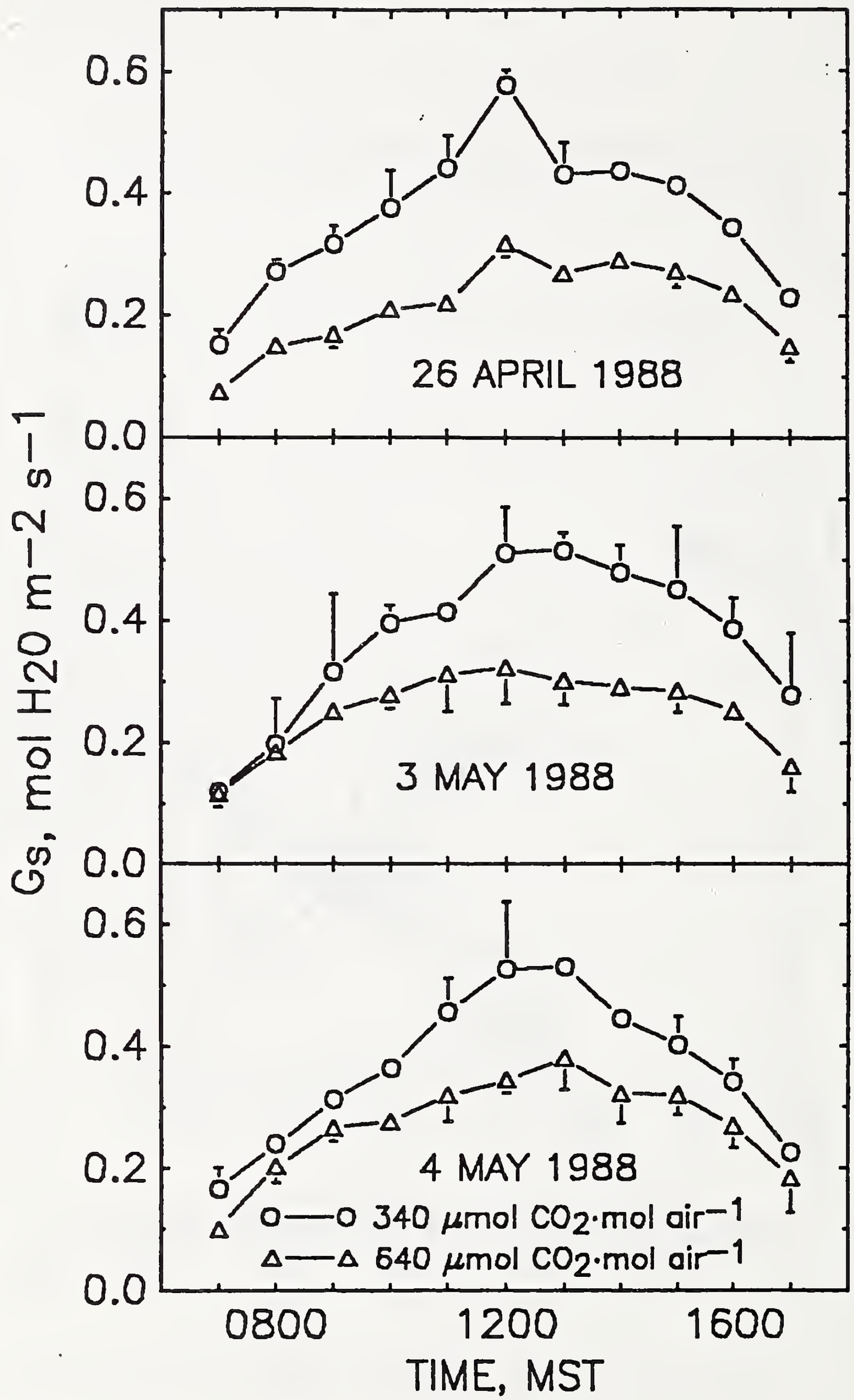

Fig. 6. Stomatal conductance of water vapor (Gs) of sorghum in ambient CO_2 and 640 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 4 May 1988. Bars represent standard deveiation.

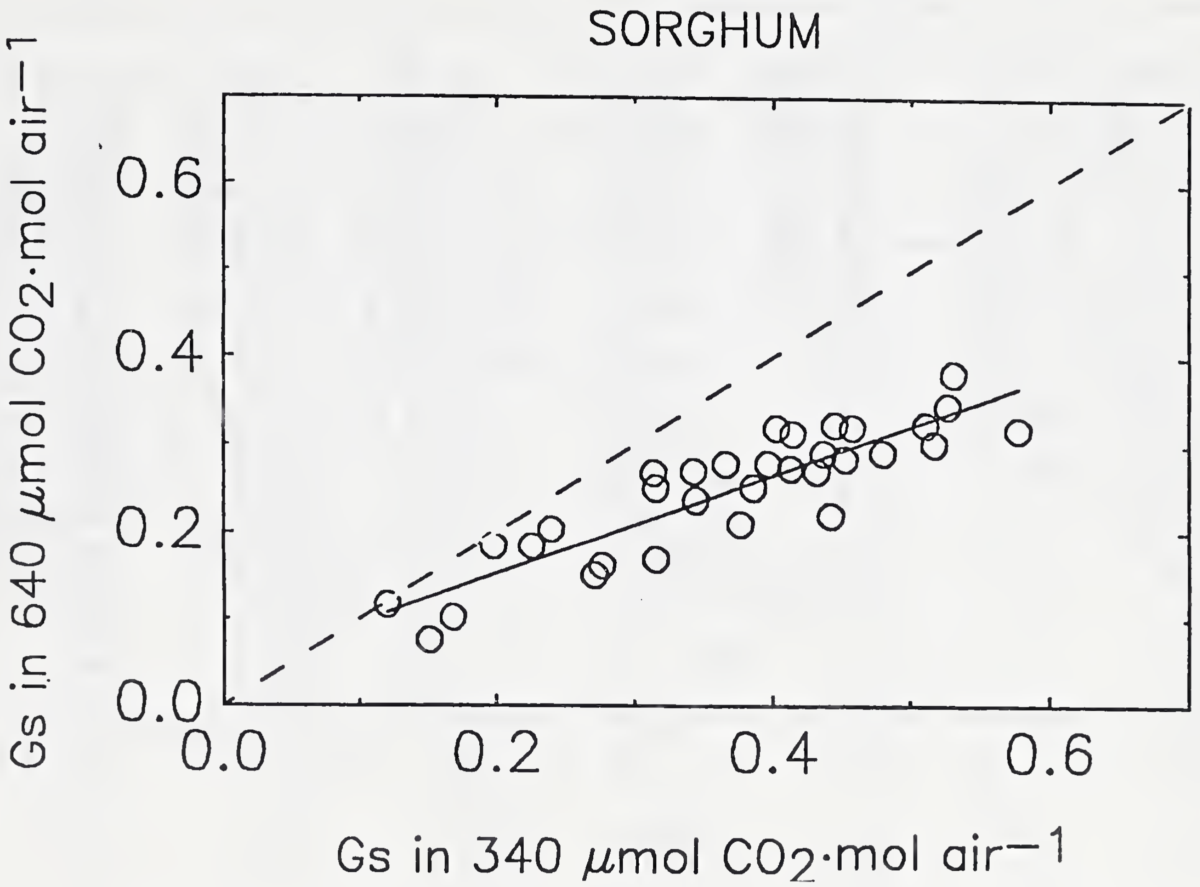

Fig. 7. Linear regression of stomatal conductance of water vapor (Gs) of sorghum in 640 versus 340 μmol CO_2 mol air^{-1}. n = 33; slope = 0.57, signfificantly different from 1.00 at $P < 0.05$.

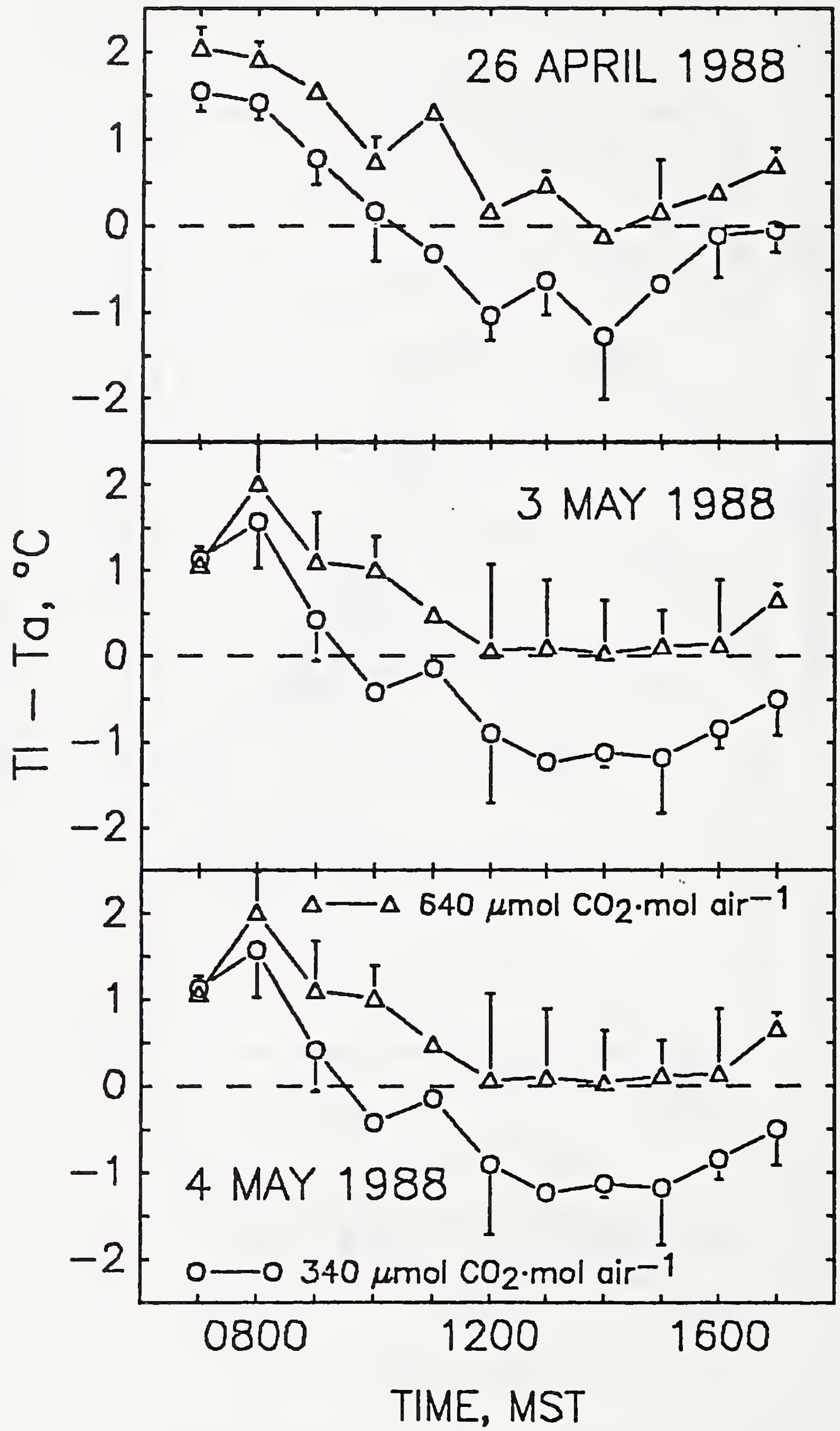

Fig. 8. Temperature differential between leaf and air (Tl - Ta) of sorghum in ambient CO_2 and 640 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 5 May 1988. Bars represent standard deviation.

List of Figures

TITLE: BROMIDE RECOVERY FROM MOHALL SILT LOAM SOIL

SPC: 1.33.302.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-11130-003

INTRODUCTION

A proposed experiment involved the availability of a minimal amount of soil sample. Therefore the necessity of sample conservation dictated the use of one aliquot for determination of both moisture content and bromide quantification. An additional benefit obtained by performing both analyses on the same aliquot would be the elimination of subsampling errors due to moisture content variation among aliquots.

Information was needed concerning the effects of oven drying 24 hours @ 104° C on bromide recovery from Mohall silt loam soil obtained from the Maricopa farm. The soil series is a Mohall sandy loam (fine loamy mixed hyperthermic Typic Haplargids). The average bulk density at 0-3 cm = 1.48 $\pm$ 0.007 mg m^{-3} .

MATERIALS AND METHODS

I. Test Tube Samples - Preliminary Check to Determine Bromide Recovery.

Three 20 gram Mohall sandy loam silt soil aliquots $\leq$ 2 mm particle size were oven dried for moisture content determination.

Twenty-four 20 gram aliquots of air-dried soil were placed in polypropylene centrifuge tubes. Twenty ml of 0, 5, 10, 25, 50, and 100 ppm bromide in tap water solutions (prepared from potassium bromide) were added in quadruplicate. Four extra tubes with 20 ml tap water each, were used for blanks. All tubes were placed horizontally on a mechanical shaker @ low speed 1 hour. All tubes were centrifuged @ 14,000 rpm 1 hour. $\approxeq$ 3 ml supernatant liquid from each tube was removed with Pasteur pipette. All bromide additive solutions and extract bromide solutions were analyzed for bromide with Technicon Autoanalyzer and with HPLC.

II. Column Soil Samples

Each of 5 plexiglass columns 4.5 cm ID X 26 cm height was prepared by plugging one end with a # 10 rubber stopper into which a glass tubing 0.5 cm ID X 9 cm length was inserted as a drain. A small piece of glass wool was inserted at the top end of the drain tube. A 4.3 cm diameter tightly woven cloth disc was placed over the rubber stopper. The glass wool and cloth disc served as a barrier to sand entering the drain tube.

Three-hundred gram air-dried Mohall silt loam soil $\leq$ 2 mm particle size, was placed into each column. The columns were gently tapped to create a uniform height of 14.3 cm. Another cloth disc followed by a 4.3 cm disc of nylon mesh window screen was placed over the soil to minimize disturbance of the soil when the solution was later added. Volume of

soil: radius=21.5, height=143 cm, weight of soil=300 grams air dried, volume = 207.665 cc, density=300 g/207.665=1.44464.

Columns were labeled for 0, 5, 10, 25, and 50 ppm bromide.

Initially, 180 ml solution was added to each column and allowed to drain. Eluent was taken for bromide analysis. One hundred-sixty ml wa added to each column 9 times. Effluent samples for bromide analysis wer taken from each drainage.

The final drainage time for all columns was approximately 62 hours (weekend). The content of all columns was emptied into separate self-sealing plastic bags. After thorough mixing, three 20 gram aliquots from each concentration were placed into 50 ml polypropylene screw cap centrifuge tubes. Twenty ml tap water was added to each tube.

Three 20 gram aliquots from each concentration were placed into drying tins and oven dried @ 104°C for 24 hours to determine moisture content. After dry weights were recorded, the soil was placed into polypropylene centrifuge tubes. The tins was rinsed twice with 10 ml tape water. This rinse was added to the tubes. All tubes were mixed in horizontal position 2 hours @ low speed on a mechanical shaker. All tubes were centrifuged @ 14,000 rpm 1 hour. ≊ 3 ml supernatant liquid from each tube was removed with Pasteur pipette and analyzed for bromide using Technicon Autoanalyzer and HPLC.

III. HPLC Conditions

Waters 6000A Pump
Waters 480 UV Detector at 205 nm.
Waters RCM with SAX10 Cartridge
Perkins-Elmer LCI100 Integrator
Perkins-Elmer ISS100 Autosampler

Mobile phase: 0.01 M KH_2PO_4 in Type I water
pH: 2.8
organic: 10% CH_3CN v/v
flow rate: 2 ml/min

IV. Calculations

1) added solution - test tube samples

$$\text{mg Br}^-/\text{g soil} = \frac{cv}{d \times 1000}$$

where c = ppm concentration of solution added
v = volume of solution added
d = oven-dried soil weight

2) soil moisture factor for test tube recovery samples

$$\bar{x}\ H_2O/20g\ \text{soil} = 0.467g\ H_2O/20g\ \text{soil}$$

$$\text{mg}/Br^-/\text{mg soil} = \frac{0.467 + 20}{20 - 0.467}\ X\ \text{reading} = 1.048656\ X\ \text{reading}$$

$$\text{mg}/Br^-/\text{g soil} = 1.048656/1000\ X\ \text{reading}$$

3) mg Br^-/g dry soil for test tube samples

$$\frac{A + B}{S - A}\ X\ \frac{B}{1000}$$

A = average weight loss of oven-dried aliquot
B = ml bromide added
S = g air-dried soil
R = analytical reading

4) saturated soil column samples

$$\frac{c\ s}{d\ X\ 1000}$$

c = concentration of solution added
s = ml saturated soil moisture
d = dry soil weight

5) oven-dried column soil

$$\frac{cv}{d\ X\ 1000}$$

c = concentration of solution added
v = volume of solution added
d = oven-dried soil weight

RESULTS AND DISCUSSION

Test Tube Samples

The results of the preliminary test tube check for bromide recovery from air-dried soil with bromide solution added in test tubes are presented in Figure 1 and Tables 1 and 2. The Technicon Autoanalyzer procedure results were 98.6% to 126.4% (Table 1) using all data collected. Since not all aliquots of the same concentration are involved, it appears the

3 abnormally high values† are due to contamination of the tubes from previous use. The zero value on the soil blanks eliminates the possibility of negative interference which sometimes occurs with the procedure (Annual Report 1984). Omitting the 3 contaminated readings gave recoveries of 95% to 101%. These results seem reasonable when considering methodology variation.

The tube contamination explanation is substantiated by the HPLC higher values‡ for the same 3 aliquots.

The higher than expected HPLC readings (Table 2) are not due to nitrite and/or chloride since nitrite eluted at 5.29 minutes and chloride at 8.29 minutes, well before bromide at 16.77 minutes. Nitrate eluted at 14.26 minutes with the conditions used, therefore some possibility of nitrate interference exists. A small peak at the bromide elution time is frequently found on soil blanks. The high nitrate readings may have concealed the interference readings on the zero bromide addition samples.

Using all the HPLC data, the $\bar{x}$ recovery of bromide was 132%. Omitting the 3 contaminated values gave a $\bar{x}$ recovery of 123.5%. Using the interference in the tube tap water blanks as a correction factor, does not decrease the value sufficiently to be reasonable percentage-wise.

Column Soil

The Technicon data for saturated column soil recovery (Table 3) indicates recoveries ranging from 72% to 88% with concentration $\bar{x}$ recovery values of 75% to 85%; the oven dried recovery (Table 4) ranged from 52% to 75% with concentration $\bar{x}$ values of 54% to 75% (Figure 2).

The HPLC data gave $\bar{x}$ concentration recoveries (Table 5) of 70% to 91% for saturated column soil; the oven dried recovery (Table 6) ranged from 73% to 88% (120% is likely contamination) with $\bar{x}$ concentration recoveries 76% to 86% and Figure 3.

The Technicon Autoanalyzer analysis of bromide in soil column effluent for each drainage is shown in Table 7 and the HPLC analysis in Table 8. The ratio of bromide in effluent to bromide in eluent range is 91.2% to 107% for Technicon Autoanalyzer and 94.5% to 147.6% for HPLC, with the first drainage having the highest reading for each concentration. The higher first values are likely due to anion exclusion of bromide.

PERSONNEL

G. C. Auer

Table 1. Test tube recovery - Technicon — Bromide recovery 032089

ppm Br^- solution added	ppm Br^- final supernatant solution	$\frac{\text{mg } Br^- \text{ added}}{\text{g dry soil}}$	recovery mg Br^-/g dry soil	% recovery	$\bar{x}$	S
0.0	0.0	0.0	0.0			
0.0	0.0	0.0	0.0			
0.0	0.0	0.0	0.0			
0.0	5.0	0.0	0.00524328			
5.0	7.8	0.00511954	0.00817297	159.643	126.384	32.763
5.0	9.3	0.00511954	0.00764906	149.409		
5.0	4.8	0.00511954	0.00502952	98.242		
5.0	4.8	0.00511954	0.00502952	98.242		
10.067	9.5	0.01030768	0.00954257	92.577	102.198	15.487
10.067	9.5	0.01030768	0.00954257	92.577		
10.067	9.7	0.01030768	0.0101638	98.604		
10.067	12.3	0.01030768	0.01288814	125.034		
25.4	24.4	0.02600727	0.0255667	98.306	98.608	0.3858
25.4	24.6	0.02600727	0.02577629	99.112		
25.4	24.4	0.02600727	0.0255667	98.306		
25.4	24.5	0.02600727	0.0256715	98.709		
50.6	51.0	0.051809758	0.05343864	103.144	101.627	1.0509
50.6	49.8	0.051809758	0.05218126	100.717		
50.6	50.1	0.051809758	0.0524956	101.324		
50.6	50.1	0.051809758	0.0524956	101.324		
103.35	97.9	0.10582092	0.1025812	96.938	99.028	2.1432
103.35	99.0	0.10582092	0.1037338	101.434		
103.35	98.5	0.10582092	0.10321	97.533		
103.35	101.2	0.10582092	0.106039	100.206		

Table 2. Test tube recovery - HPLC Bromide recovery 032089

ppm Br^- solution added	ppm Br^- final supernatant solution	mg Br^- added / g dry soil	recovery mg Br^-/g dry soil	% recovery	$\bar{x}$	S
0.0	0.0	0.0				
0.0	0.0	0.0				
0.0	0.0	0.0				
0.0	7.435	0.0				
5.0172	10.6399	0.00513636	0.1115759	217.228	182.836	36.641
	10.3727	0.00513636	0.01087739	211.772		
	7.4577	0.00513636	0.00782056	152.259		
	7.3513	0.00513636	0.00770898	150.086		
10.2932	12.8966	0.01023908	0.0135241	132.083	143.113	17.661
	13.0151	0.01023908	0.01364836	133.297		
	13.4467	0.01023908	0.01410096	137.717		
	16.5357	0.01023908	0.01734026	169.354		
25.8397	29.5245	0.0264534	0.03096104	117.04	118.672	1.298
	30.0113	0.0264534	0.03147153	118.97		
	29.8924	0.0264534	0.0313468	118.498		
	29.9232	0.0264534	0.03137914	120.179		
50.8575	57.6796	0.05206537	0.06048606	116.173	111.313	3.813
	55.0919	0.05206537	0.05777245	110.961		
	53.0535	0.05206537	0.05563487	106.856		
	55.2405	0.05206537	0.05792828	111.261		
100.298	105.2992	0.1028008	0.1104226	107.414	108.438	1.729
	114.0418	0.1028008	0.1140418	110.935		
	105.0418	0.1028008	0.1101527	107.152		
	106.1208	0.1028008	0.1112842	108.252		
tap water tube blank	0.106				0.1219	0.0186
	0.106					
	0.1342					
	0.1413					

Table 3. Saturated column soil - Technicon — Bromide recovery 032989

ppm Br^- eluent	H_2O/soil	mg Br^-/g dry soil	theoretical mg Br^-/g dry soil	% recovery	$\bar{x}$ recovery	S
0	1.63911	0.0	0.0			
0	1.63911	0.0	0.0			
0	1.63911	0.0	0.0			
5	1.60473	0.00123311	0.00151182	81.565	81.565	0.0
5	1.60473	0.00123311	0.00151182	81.565		
5	1.60473	0.00123311	0.00151182	81.565		
10	1.63864	0.00245796	0.00319261	76.989	75.247	3.01
10	1.63864	0.00245796	0.00319261	76.989		
10	1.63864	0.0022941	0.00319261	71.763		
25	1.607007	0.00626733	0.00758815	82.594	82.947	0.611
25	1.607007	0.00634768	0.00758815	83.653		
25	1.607007	0.00626733	0.00758815	82.594		
50	1.62528	0.01300224	0.01563002	83.188	84.574	2.401
50	1.62528	0.01300224	0.01563002	83.188		
50	1.62528	0.013652352	0.01563002	87.347		
			$\bar{x}$	81.00		4.048

Table 4. Oven-dried column soil - Technicon Bromide recovery 032989

ppm Br^- eluent	H_2O/dry soil	mg Br^-/g dry soil	mg Br^- added/ dry soil	% recovery	$\bar{x}$ recovery	S
0	1.31579	0.0	0.0			
0	1.32275	0.0	0.0			
0	1.2903	0.0	0.0			
5	1.30208	0.00097656	0.00151042	64.655	67.412	17.47
5	1.30293	0.00078176	0.00151466	51.613		
5	1.30208	0.00130208	0.00151042	86.2067		
10	1.31492	0.0017094	0.003149	54.28	53.742	1.347
10	1.33156	0.00173103	0.00331558	52.209		
10	1.311475	0.00170492	0.00311475	54.737		
25	1.29955	0.00493829	0.00748863	65.944	65.856	0.159
25	1.30634	0.00502941	0.00765839	65.672		
25	1.30463	0.00502283	0.00761579	65.953		
50	1.31752	0.0117918	0.01587615	74.274	74.883	0.603
50	1.30634	0.01156111	0.01531679	75.48		
50	1.31406	0.01176084	0.01570302	74.895		

Table 5. Saturated column soil - HPLC　　　Bromide recovery 032989

ppm Br^- eluent	H_2O/soil	mg Br^-/g dry soil	mg Br^- added/ g dry soil	% recovery	$\bar{x}$ recovery	S
0.0	1.63911	0.0	0.0			
0.0	1.63911	0.0	0.0			
0.0	1.63911	0.0	0.0			
4.9716	1.60473	0.00119601	0.00149928	79.772	79.405	1.47557
4.9716	1.60473	0.00116616	0.00149928	77.781		
4.9716	1.60473	0.0012004985	0.00149928	80.663		
10.0439	1.63864	0.0021363878	0.00320663	69.033	70.467	2.1989
10.0439	1.63864	0.0023407972	0.00320663	72.999		
10.0439	1.63864	0.002224454	0.00320663	69.370		
24.84	1.607007	0.006864813	0.00753959	91.050	84.056	6.0618
24.84	1.607007	0.006092646	0.00753959	80.809		
24.84	1.607007	0.006055042	0.00753959	80.31		
49.5973	1.62528	0.01406241	0.01550414	90.701	90.517	0.1765
49.5973	1.62528	0.01403137	0.01550414	90.501		
49.5973	1.62528	0.0140078	0.01550414	90.349		
			$\bar{x}$	81.112		8.13306

Table 6. Oven-dried column soil - HPLC Bromide recovery 032989

ppm Br^- eluent	mg Br^-/dry soil	mg Br^- added/ g dry soil	% recovery	$\bar{x}$ recovery	S
0.0	0.0	0.0			
	0.0	0.0			
	0.0	0.0			
4.9716	0.001172	0.001501838	78.04	79.54	2.114
4.9716	0.00122032	0.00150605	81.03		
4.9716	0.00179609	0.001501838	119.59	92.887	23.174
10.0439	0.0024519	0.003161526	77.55	76.34	2.645
10.0439	0.0024414	0.003330135	73.31		
10.0439	0.00244564	0.003128428	78.17		
24.84	0.006061	0.0074407	81.46	81.91	2.52
24.84	0.0063462	0.00760938	79.65		
24.84	0.0064042	0.007567045	84.63		
49.5973	0.01352928	0.01574829	84.84	85.86	1.799
49.5973	0.0133607	0.0151934	87.94		
49.5973	0.0132103	0.01557655	84.81		
			$\bar{x}$	84.249	11.9578

Table 7. ppm Br^- column soil effluent - Technicon Bromide recoverey 032989

effluent sample	1	2	3	4	5	6	7	8	9	10
eluent concent.	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5 ppm	5.3	4.65	4.8	4.9	4.8	4.8	4.8	4.8	4.8	4.8
10 ppm	10.6	9.8	9.9	9.9	9.9	9.9	9.85	9.9	9.9	9.95
25 ppm	26.8	24.0	24.2	24.0	24.2	24.0	24.0	23.8	24.0	22.8
50 ppm	52.0	49.8	49.2	48.8	48.6	48.0	47.6	48.4	48.0	48.0

Table 8. ppm Br^- column soil effluent - HPLC Bromide recovery 032989

effluent sample	1	2	3	4	5	6	7	8	9	10
eluent concent.										
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4.9716	8.8587	4.9018	4.825	4.8021	4.9616	4.7979	4.8655	4.7616	4.8258	4.8217
10.0439	14.8238	10.1252	10.0624	9.8435	10.0694	9.7159	9.6728	9.5278	9.4939	9.5885
24.84	31.4516	24.5432	24.5929	25.3586	25.0068	24.192	23.8135	23.9362	24.6845	24.6462
49.5973	59.0268	49.0888	50.3735	50.085	50.7553	51.3568	50.1607	49.7166	49.9578	50.1284

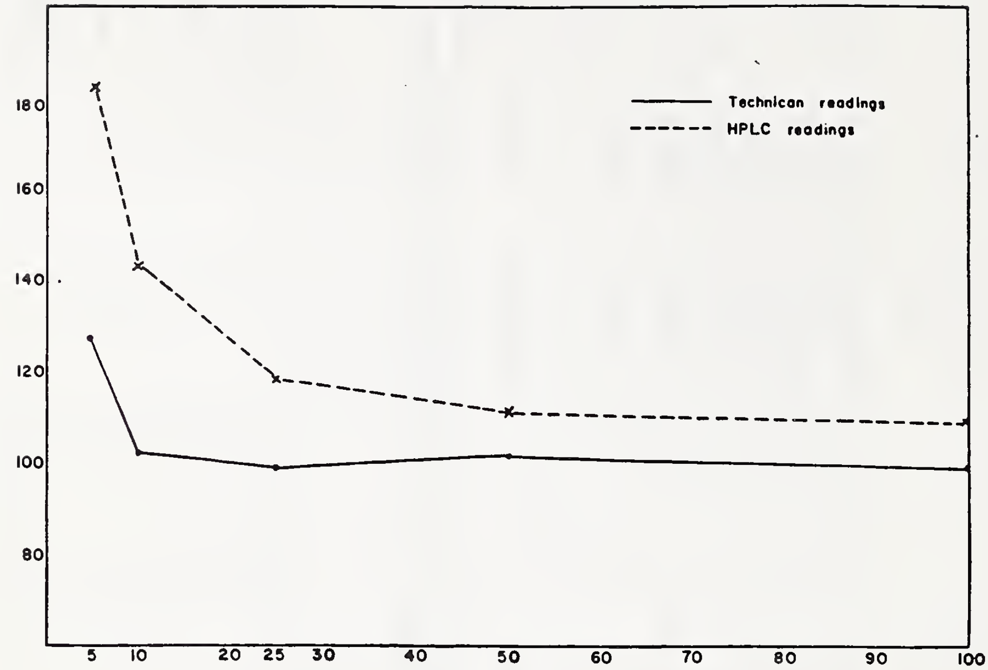

Figure 1. $\bar{x}$ % bromide recovery from soil tube samples 3-29-89

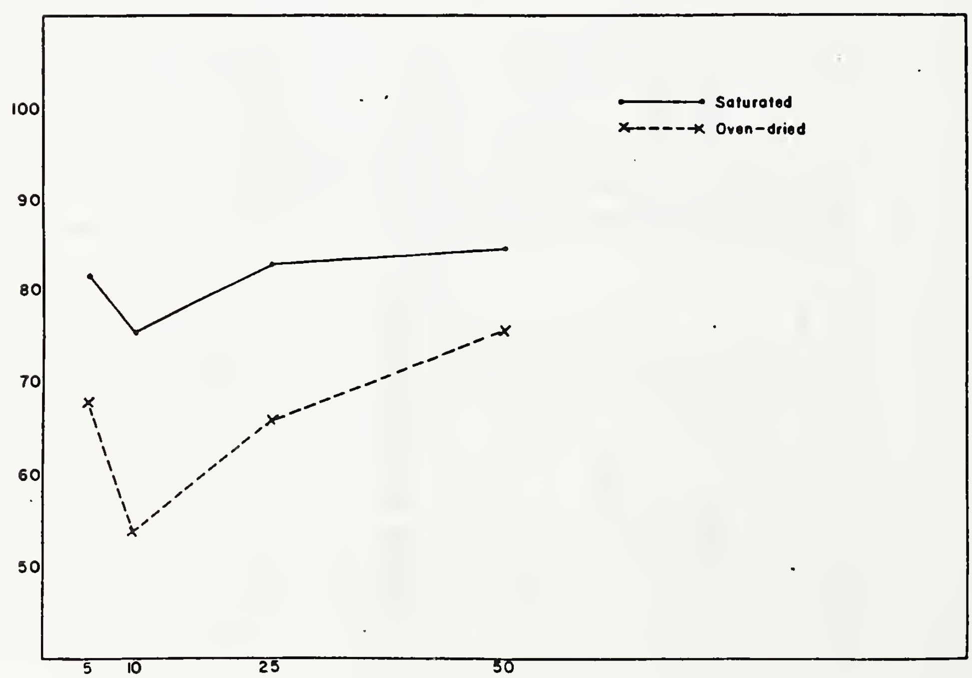

Figure 2. $\bar{x}$ % bromide recovery 3-29-89 (technician analysis)

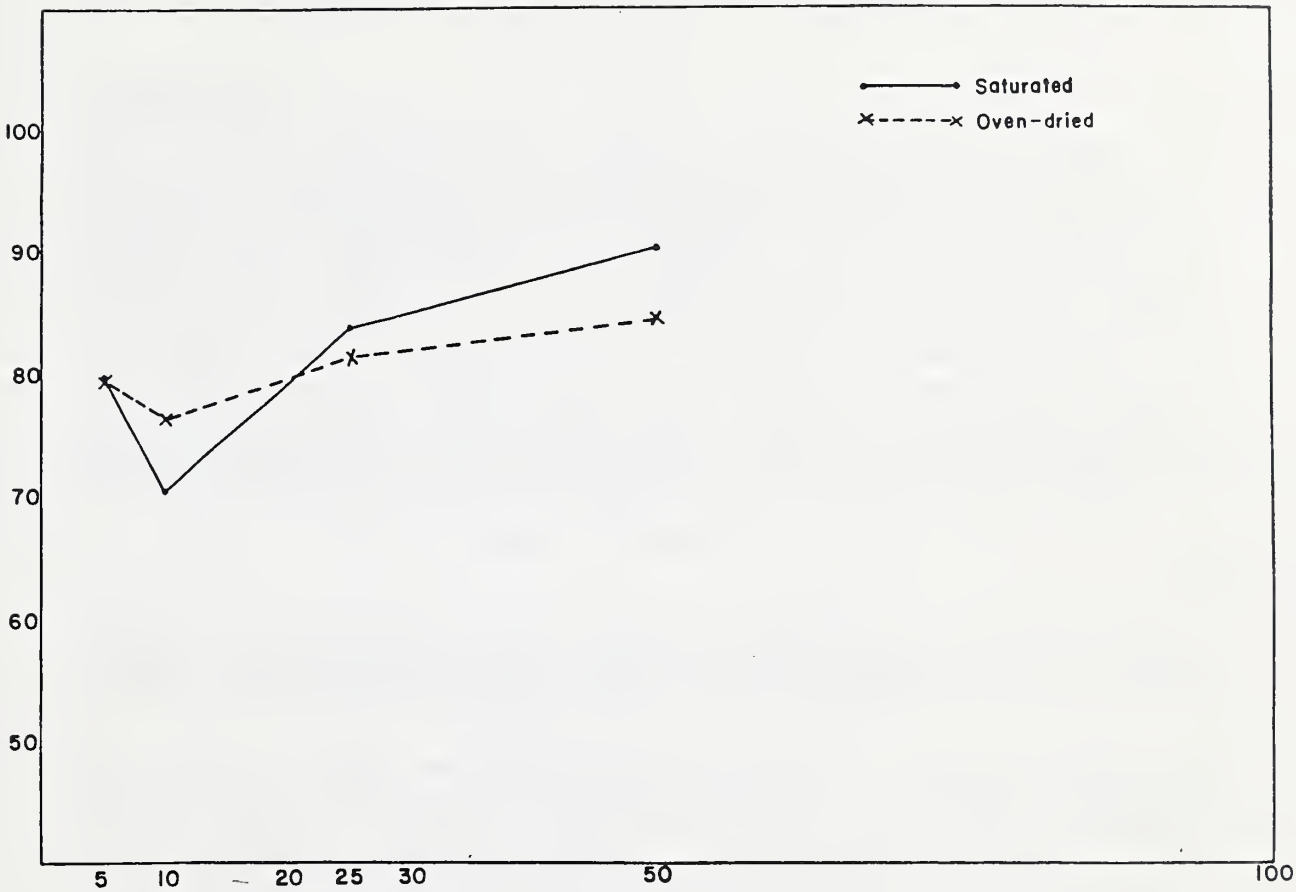

Figure 3. $\overline{x}$ % bromide recovery 3-29-89 (HPLC analysis)

TITLE: Independent Calibration of a Deterministic - Stochastic Model For Field-Scale Solute Transport: Results from Two Field Experiments

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-11130-003

INTRODUCTION

For vertical infiltration and leaching, Dagan and Bresler (1979) proposed a simple model for describing the movement of conservative solutes at the field-scale. In this model, the field is completely divided into a number of parallel vertical soil- or stream-columns, for which several assumptions are made regarding solute transport. These assumptions include: (i) the hydraulic properties within each column are constant and uniform with depth, but that (ii) the hydraulic properties vary from stream-column to stream-column across the field in a stochastic manner, (iii) each stream-column is isolated from its nearest neighbors (no horizontal flow), thus (iv) we can describe solute transport with the one-dimensional advection - dispersion equation

$$\partial c/\partial t = D\, \partial^2 c/\partial x^2 - v\, \partial c/\partial x \tag{1}$$

where c is the resident solute concentration (g/m_1^3), t is time (d), D is the dispersion coefficient (m^2/d), x is the depth below the surface (m), and v is the average pore water velocity (m/d).

This model has been used by Amoozegard-Fard et al. (1982), Parker and van Genuchten (1984), and Persaud et al. (1985) to describe field-scale solute transport. However, in the first two studies, the variability in v between stream-columns was found to completely dominate the contribution from the dispersion term in dispersing the solute at the field scale. Therefore, following the suggestion of Dagan and Bresler (1979), D can be set equal to 0.0 in Eq. 1 giving

$$\partial c/\partial t = -\, v\, \partial c/\partial x \tag{2}$$

which is equivalent to piston flow within each stream-column.

For a conservative solute, that is initially sprayed uniformly on the soil surface and then leached through the soil, the initial and boundary conditions can be expressed as

$$\begin{aligned} c(x,0) &= c_1, \qquad 0 \le x \le \Delta x \\ &= c_o, \qquad x > \Delta x \\ c(0,t) &= c_o, \qquad t > 0 \end{aligned} \tag{3}$$

where c_o is the initial solute concentration in the soil, c_1 is the concentration of the solute being sprayed on the soil, and Δx is the

effective depth of soil within which the applied tracer initially resides. This depth is calculated from

$$\Delta x = M/(c_1 \theta) \tag{4}$$

where M is the mass of solute applied per unit area (g/m^2) and θ is the average volumetric water content, which for simplicity is assumed constant for all stream-columns over time and space. Equation 2 subject to Eq. 3 can be solved by inspection with the result that concentrations equal to c_1 will propagate down through the stream-column within the limits

$$0 \leq x - vt \leq \Delta x \tag{5}$$

However, since v varies from stream-column to stream-column the field-wide solute concentration for any time and depth is found by integrating over all possible velocities (Parker and van Genuchten, 1984)

$$c(x,t) = \frac{\int_0^{\frac{x-\Delta x}{t}} c_0 \rho(v)\, dv + \int_{\frac{x-\Delta x}{t}}^{x/t} c_1 \rho(v)\, dv + \int_{x/t}^{\infty} c_0 \rho(v)\, dv}{\int_0^{\infty} \rho(v)\, dv} \tag{6}$$

where $\rho(v)$ is the probability density function (PDF) for the velocity. Using a log-normal distribution for $\rho(v)$ in Eq. 6 (Biggar and Nielsen, 1976) we have

$$c(x,t) = \frac{c_1}{\sigma(2\pi)^{½}} \int_{\frac{x-\Delta x}{t}}^{x/t} 1/v \exp \frac{-(\ln v - \mu)^2}{2\sigma^2}\, dv \tag{7}$$

where μ and σ^2 are the mean and variance of the log-transformed velocity. Thus there are only two parameters, $\mu_{\ln v}$ and $\sigma^2_{\ln v}$, we need to estimate before applying the model to field-scale solute leaching.

In the past, Eq. 7 has been used to describe field-scale solute transport, but the model parameters were fit to the measured data and

effective depth of soil within which the applied tracer initially resides. This depth is calculated from

$$\Delta x = M/(c_1\theta) \tag{4}$$

where M is the mass of solute applied per unit area (g/m^2) and θ is the average volumetric water content, which for simplicity is assumed constant for all stream-columns over time and space. Equation 2 subject to Eq. 3 can be solved by inspection with the result that concentrations equal to c_1 will propagate down through the stream-column within the limits

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$$c(x,t) = \frac{\int_0^{\frac{x-\Delta x}{t}} c_0\rho(v)\,dv + \int_{\frac{x-\Delta x}{t}}^{x/t} c_1\rho(v)\,dv + \int_{x/t}^{\infty} c_0\rho(v)\,dv}{\int_0^{\infty} \rho(v)\,dv} \tag{6}$$

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In the past, Eq. 7 has been used to describe field-scale solute transport, but the model parameters were fit to the measured data and

thus the model was of little use as a predictive tool. However, if it were possible to estimate the parameter values independent of any leaching experiment, than Eq. 7 could be transformed into a truly predictive model for field-scale transport. In this paper we review a method for estimating the model parameters described by Jaynes et al., (in press) and examine the success of the model to predict the field-scale transport of a conservative tracer in two field experiments.

PARAMETER ESTIMATION

For the stream-column model, v is uniform within each column. If we treat evaporation as a deficit that accumulates at the surface and must be replenished before water moves through the profile (Rose et al., 1982), then v, averaged over time, is equal to the total depth of water that has infiltrated the surface, I, minus previous evaporation, S, divided by the time since leaching started, t_o, and the mobile water content, θ_m,

$$v = (I-S)/\theta_m t_o = I_e/\theta_m t_o \tag{8}$$

where I_e is the effective infiltration. If we assume that evaporation is proportional to the infiltration distribution or

$$S = \alpha I \tag{9}$$

and Eq. 8 becomes

$$v = I(1-\alpha)/\theta_m t_o = \beta I/\theta_m t_o \tag{10}$$

For a log-normally distributed v with β, θ_m, and t_o constant for each stream-column, the mean of the log-transformed velocity is

$$\begin{aligned}\mu_{\ln v} &= \mu_{\ln I} + \ln \beta - \ln \theta_m - \ln t_o \\ &= \mu_{\ln I_e} - \ln \theta_m - \ln t_o\end{aligned} \tag{11}$$

and the variance is

$$\sigma^2_{\ln v} = \sigma^2_{\ln I} \tag{12}$$

Thus if the infiltration and evaporation histories are known and θ_m can be estimated, the model can be calibrated directly without the need of a solute transport experiment.

FIELD EXPERIMENTS

The model was tested against leaching experiments conducted at two sites, a sandy loam soil and a uniform medium sand. Details of the solute transport experiments can be found in Rice et al. (1986 and in preparation) and are only summarized here. The first experiment, conducted on a sandy loam, consisted of a 0.62 hectare field divided into 56, 12.2- by 9.15-m subplots. Fourteen subplots were chosen in a stratified-random manner on each of which 2.24 kg of KBr dissolved in 20 L of water was uniformly sprayed with a hand-operated spray rig. The Br^- was then leached through the soil profile with eight flood irrigations over a 159 day period. At six times during this period, samples from two locations within each subplot were taken and analyzed for Br^- concentration. Samples were taken in 0.3-m increments with a 0.021-m diameter sampling tube down to a depth of 2.7-m.

A neutron access tube was installed in the 14 subplots to a depth of approximately 3 m and water content measurements were measured periodically during the experiment. Evaporation rates were calculated using the energy balance technique described by Jackson et al. (1976).

In the second experiment an approximately 37- x 3.7-m plot was located on a uniform sand. The plot was subdivided lengthwise into four subplots by soil berms in order to better control irrigation. Neutron probe access tubes were located in the center of two of the subplots to a depth of 2.7 m and water content were measured periodically. A solution containing 433 g KBr dissolved in 16 L of water was sprayed on to each subplot. The bromide was then leached with five irrigations over a 49-day period. Soil samples were taken six times during the experiment at approximately one week intervals. The samples were taken with a 0.021-m diameter sampling tube down to a depth of 1.8 m on the first sampling date and to a depth of 2.7 m on the subsequent dates. Samples were taken in 0.3-m increments except on the first two dates when 0.15-m increments were taken for the first two samples followed by 0.3-m increments.

Infiltration variability was measured after the solute transport phase of each experiment was completed. Falling head infiltration rates were measured inside 0.254-m diameter ring infiltrometers. The water depth inside each ring was measured every two minutes with the bubbler head-measuring system described by Dedrick and Clemmens (1984). Infiltration measurements were made with falling heads in order to more closely reproduce the irrigation method used during the Br^- leaching experiment. The surrounding subplots were irrigated with an equal depth of water at the same time the infiltrometers were filled to serve as outer guard rings. Total water applied within the rings and subplots was 0.13 m. For the sandy loam soil 63 infiltrometers were located on a regular 7- by 9-m grid with 1-m spacings. On the sand, 71 infiltrometers were located along a single discontinuous transect with a 0.5-m spacing between rings.

Regression curves were fit to the infiltration depth (I) versus time curves for each infiltrometer by a non-linear least-squares method (Jaynes, 1987). The Kostiakov infiltration function was used to describe the data since it is a simple two parameter equation and gave good fits to the measured data with $R^2 > 0.93$ for each curve. Regression equations were used only to give estimates for infiltration depths at fixed times.

MODEL CALIBRATION

Estimating $\mu_{\ln v}$

The mean velocity was calculated from the mean depth of water applied during each irrigation and calculated evaporation. The cumulative μ_I corresponding to each sampling date is listed in Table 1 for the two fields. Individual irrigations varied from 50 to 100 mm on the sandy loam site and from 66 to 100 mm on the sand site. No rain fell during the experiment on the sand site, while a total of 59 mm fell during three rain events on the sandy loam site. The rain did not contribute significantly to Br^- leaching however, since it was less than the evaporation since the previous irrigation. The cumulative mean effective infiltration depth for each date is also shown in Table 1. Effective infiltration decreased steadily throughout the experiment on the sandy loam site due to an increase in evaporation as the season progressed from winter into summer. Table 1 lists μ_v and $\mu_{\ln v}$ based on I_e, the infiltration variance, and the mobile water content (see below). Velocities decreased throughout the experiment on the sandy loam soil. The very large calculated velocity at day 5 is due to the sampling occurring only 5 days after the first irrigation (Eq. 10). Velocities for the leaching experiment on the sand site showed no obvious trends, but were instead relatively constant throughout the measurement period.

Estimating $\sigma^2_{\ln v}$

The variances of the pore water velocities for the two fields were estimated from the results of the infiltrometers. Infiltration rates as measured with the infiltrometers were extremely variable for the two soils. Figure 1 shows the depth of water infiltrated inside the 63 infiltrometers over the first 15 minutes on the sandy loam. Values for I at the end of 15 minutes ranged from 9 to 142 mm. Infiltration curves for the 71 infiltrometers located on the sand are shown in Fig. 2 also for the first 15 minutes of infiltration. Infiltration was considerably less variable for the sand than for the sandy loam soil, with a minimum infiltration depth of 44 mm and a maximum infiltration depth of 97 mm after 15 minutes.

Values of $\sigma^2_{\ln I}$ for the sandy loam and sand corresponding to the average irrigation depths were used to calibrate the model rather than the variances corresponding to the mean depth applied for each individual irrigation. However, these values changed little over the range of irrigations applied (50 - 100 mm, Fig. 3) and single values

were used for convenience. For the single subplot measured at the sandy loam site, 14.7 minutes were required to infiltrate the average irrigation depth of 58.3 mm. At the sand site, times of 13.9, 14.2, 19.0, and 24.2 minutes were required to infiltrate the average irrigation of 78.8 mm into the four subplots.

Figures 4 and 5 show the histograms for the I values from the two sites and the corresponding normal and log-normal distributions. Both distributions fit the measured histogram well, although the log-normal curves fit better near the tails of the distribution and don't predict negative values for infiltration depth as do the normal distributions. A log-normal distribution was thus assumed to characterize the infiltration and pore water velocity distributions for both soils.

Calculated values for $\sigma^2_{\ln I}$ equaled 0.313 for the sandy loam and 0.0236 for the sand. The values for $\sigma^2_{\ln I}$ from the infiltration measurements cannot be used directly in Eq. 11 however, since the infiltration values were measured over a larger area or support (ring diameter of 0.254 m) than that for the Br^- measurements (sampler diameter of 0.021 m). Since the infiltration measurements integrate the spatial variability of the soil over a larger area than the Br^- measurements, they may underestimate the true value of σ^2 on the scale used to measure Br^- leaching. It would be tempting to correct for the difference caused by support size by invoking the central limit theorem to correct the σ^2 values, however this may result in biased estimates if the velocities are spatially correlated (Sisson and Wierenga, 1981).

To examine the spatial variability of the infiltration data, semi-variograms were calculated using the ln I data for the two soils (Journel and Huijbregts, 1978). The semi-variance, N(h), was calculated from

$$\gamma(h) = \frac{1}{2N(h)} \sum^{N(h)} [\ln I(x_i) - \ln I(x_i + h)]^2 \tag{13}$$

where h is the distance (m) separating the experimental ln I values located at x_i and x_i+h and N(h) is the total number of pairs separated by h.

The experimental variograms for the two soils were examined for linear trends and, in the case of the sandy loam, for anisotropy (Journel and Huijbregts, 1978). No trends were found, but a simple geometric anisotropy was detected in the sandy loam variogram which was removed before theoretical variograms were fit to the data. A spherical model was fit to each experimental variogram using a jackknife procedure to obtain a kriged average error close to zero and an average ratio of calculated to theoretical variances of 1.0 (Vauclin et al., 1983). The

resulting theoretical semi-variograms were

$$\begin{aligned} \gamma(h) &= 0.336[3/2(h/2.55) - 1/2(h/2.55)^3] & h \le 2.55 \\ &= 0.336 & h > 2.55 \end{aligned} \tag{14}$$

where no nugget value, a sill of 0.336, and range of 2.55 m was found for the sandy loam and

$$\begin{aligned} \gamma(h) &= 0.0122 + 0.0126[3/2(h/2.00) - 1/2(h/2.00)^3] & h \le 2.00 \\ &= 0.0248 & h > 2.00 \end{aligned} \tag{15}$$

where a nugget value of 0.0122, a sill of 0.0248, and range of 2.00 m was found for the sand. Experimental and theoretical variograms for the two soils are shown in Figs. 6 and 7.

The experimental semi-variograms indicate a strong spatial dependency for the infiltration data to a distance of about 2 m for both fields. Thus standard sampling statistics, that assume independent data, can not be used to correct the infiltrometer data for differences in support. To estimate σ^2, valid at the smaller 0.021 m support, we make two assumptions. First, the random function for the velocity is second-order stationary over the field and thus the sill is an estimate of the variance at the field scale. Second, we assume the semi-variogram for the 0.021-m support is also described by a spherical model and can be approximated by a point variogram.

To calculate the point variogram the theoretical variograms described by Eqs. 14 and 15 were deregularized (p. 90, Journel and Huijbregts, 1978) to give

$$\begin{aligned} \gamma(h) &= 0.057[3/2(h/.254) - 1/2(h/.254)^3] & h \le 0.254 \\ &= 0.057 + 0.336[3/2(h/2.55) - 1/2(h/2.55)^3] & 0.254 < h \le 2.55 \\ &= 0.393 & h > 2.55 \end{aligned} \tag{16}$$

for the sandy loam and

$$\begin{aligned} \gamma(h) &= 0.034[3/2(h/.254) - 1/2(h/.254)^3] & h \le 0.254 \\ &= 0.034 + 0.0123[3/2(h/2.55) - 1/2(h/2.55)^3] & 0.254 < h \le 2.55 \\ &= 0.215 & h > 2.55 \end{aligned} \tag{17}$$

for the sand. The point semi-variograms consist of two nested spherical models with no nugget.

Figure 6 shows the point semi-variogram and the semi-variogram calculated from the point semi-variogram regularized to the 0.254-m support along with the experimental and original theoretical semi-variograms for the sandy loam. Figure 7 shows the same semi-variograms for the sand. In both cases agreement is excellent between the theoretical and regularized semi-variograms. However, we should point out that the deregularization process does not produce unique results (Journel and Huijbregts, 1978). Numerous point semi-variograms could be proposed that would give reasonable agreement with the measured semi-variogram when regularized to a 0.254-m support. For Eq. 14 we have used the simplest possible model to give good results. The range of the first nested semi-variogram (0.254 m) is particularly uncertain since no measurements were made at this lag distance but instead was chosen to coincide with the diameter of the infiltrometer rings. Varying the range of the first nested semi-variogram had little effect on the composite sill value when no nugget value was postulated (sandy loam). However, for the sand, the range had a profound effect on the point semi-variogram because of the nugget effect apparent in the experimental data. Thus, the point semi-variogram in this case must be used with caution.

Letting the point variogram approximate the semi-variograms at the 0.021-m support, we see that the best estimate for the variance increases from 0.336 to 0.393 for the sandy loam and from 0.0236 to 0.0462 for the sand. For the sandy loam this is a small difference and is within the uncertainty of the estimate of the variance from such a small data set (Jaynes et al., in press). For the sand the estimate increases by almost two-fold. This large increase is due to the apparent large spatial variation at distances less than 0.5 m as expressed by the large nugget value.

Mobile Water Content

Infiltration and evaporation can be measured relatively easily but there appears to be no a priori method of estimating θ_m reliably. As a first approximation, the average water content could be used for θ_m (Biggar and Nielsen, 1976), but the results of Bowman and Rice (1986), Thomas et al., (1978) and many others have shown that θ_m can be much less than the average water content, especially for anionic tracers. In a single grained sand, the fraction of the water content that does not participate in the flow process (immobile) has been shown to be highly correlated to the surface area and the double layer thickness (Krupp et al., 1972). For the sand this volume equals a water content of approximately 0.01, which was subtracted from the average water content to give the mobile water content.

For finer textured soils, especially soils with secondary units of structure, immobile water contents appear to be much higher. Addiscott (1977) and Addiscott et al. (1986) proposed a method of estimating the immobile water content by assigning water retained at potentials of -33

or -202 kPa respectively to the immobile phase. Following this general approach we estimated the immobile water content for the sandy loam by equating it to the residual water content from the water retention function and defining θ_m as the difference between this value and the average water content. Measurements of residual water made on intact soil cores gave an average value of 0.2 which was used as the estimate of the immobile water content and the mobile water content was found by difference between this value and the measured water content. Whatever the accuracy of the θ_m estimate, its value will not affect the estimate of the dispersion process since θ_m does not appear in Eq. 12.

SIMULATION RESULTS

Equation 7 was used to calculate the field-scale solute concentration profiles for the sandy loam field at the first six sampling dates where $\sigma^2_{\ln v} = 0.393$ and $\mu_{\ln v}$ was calculated from the effective infiltration and $\sigma^2_{\ln v}$ (Table 1). Figure 8 shows the results of the simulations compared to the measured values. Concentrations are given in g/m^3 of bulk soil to eliminate the effect of variable water content on the comparisons. The rectangles in Fig. 8 encompass the 95% confidence limits for the mean concentration measured over each depth increment. Measured concentrations were corrected to account for the average 14% over recovery of Br^- (Rice et al., 1986). The smooth solid curves represent the simulated results for each sampling date.

The model appears to adequately describe the solute peak position and the field-scale dispersion for the first five dates. However, the peak position is under estimated at day 126 by the model. Significantly more evaporation was calculated over this last time period, almost equalling the amount of water applied, thus the Br^- was predicted to move downward only slightly. That the observed peak continued to move rapidly may be an indication that the evaporation was over estimated and thus the effective infiltration under estimated. Observed concentrations tend to be higher near the soil surface than predicted, which may be due to an upward flux caused by evaporation. The possibility of upward fluxes is not explicitly accounted for in the model.

Results of the model are compared to the measured results on the sand in Fig. 9. The model was used with $\sigma^2_{\ln v} = 0.0462$ and the mean pore water velocity listed in Table 1. Results for the six sampling dates are shown. Agreement between the model and measured data are not as good as in the first experiment. For day 12 the model over estimates the solute peak and under estimates the degree of dispersion. Peak positions for days 18, 25, 32, and 40 appear to be closely predicted by the model but again the calculated dispersion is under estimated, although the agreement appears to improve with time. Predicted peak movement between days 12 and 18 is zero since no irrigations were applied during this period. The measured Br^- may have moved downward during this time, although it is difficult to tell since the confidence limits at the first two depths on day 12 are so large. On day 49 the measured peak appears to move upwards while the dispersion greatly increases. The

model predicts the solute to continue moving downwards and greatly under estimates the degree of dispersion. It is unclear why the solute should move upwards over the last nine days. Irrigation was more than twice the calculated evaporation during this time, thus we would expect the Br^- to continue to move downward as predicted by the model.

Possible reasons for model failure include difficulties in measuring infiltration rates with ring infiltrometers that accurately reflect the infiltration characteristics of a field (Holzapfel et al., 1988). Also we made the implicit assumption that the infiltration characteristics for these fields remained constant over the duration of the experiment. While this may be a good assumption for these fallow fields that were exposed to a minimum of rain, in general this may not be a valid assumption. Also the simple manner in which evaporation was subtracted from irrigation to obtain effective infiltration may result in considerable errors in estimating the variance. While evaporation was assumed to be proportional to infiltration, this assumption is best applied during the latter phases of evaporation when the soil hydraulic properties are the rate limiting factor. During early phases of evaporation, the evaporation rate is energy limited which implies a uniform rate of evaporation across the field. Non-proportional evaporation would tend to increase the variance of the effective infiltration and further disperse the field-scale solute profile.

Although the agreement between the model and measured Br^- profiles are not as good for the sand, results would have been much worse if the effect of the size of support of measurement had been ignored in estimating $\sigma^2_{\ln v}$ from the infiltrometer data. Two limiting cases can be proposed to illustrate this effect. As a lower bound we can assume that the measured $\sigma^2_{\ln I}$ from the infiltrometers can be used directly as an estimate of $\sigma^2_{\ln v}$, or $\sigma^2_{\ln v} = 0.0236$. As an upper bound we can assume that the hydraulic properties of the sand are completely random and that classical sampling statistics apply. In this case the variance of the infiltrometers will be N times smaller than the variance of the soil sampler where N represents the ratio of the ring area to the soil sampler area ($.254^2$ to $.021^2$). Thus this assumption gives 3.45 as an estimate of $\sigma^2_{\ln v}$. Using these estimates and the values for the mean velocities used above, Fig. 10 shows the results of the computer simulation. Agreement between the simulated and measured concentration profiles is very poor, especially for the case where the hydraulic properties are assumed to be completely random. However, Fig. 10 shows that these two limits do serve as bounds for the measured data, although the bounds are sufficiently far apart as to be of little help in predicting tracer movement.

CONCLUSIONS

For field-scale solute transport models to be of practical use, they must not only give accurate, reliable results when compared to observed behavior, but should have parameters that are easily estimated and preferably, parameters that can be estimated independently from leaching

experiments. In this study, we applied a deterministic - stochastic stream-column model to two field-scale leaching experiments in which only two model parameters were required, the mean and variance of the pore water velocity. These parameters were estimated independently from infiltration measurements, calculated evaporation, and estimated mobile water fractions. The apparent dispersion of the solute at the field scale was modelled exclusively by the spatial variation of the soil water velocity as measured by variations in infiltration.

Estimates of the variance were corrected for differences in the support size used in making the measurements of tracer leaching and infiltration. Semi-variogram analysis was used for this purpose since the infiltration properties were spatially correlated making the application of standard sampling theory invalid. For the first leaching study on a sandy loam, agreement between measured and predicted solute profiles was excellent on most of the sampling dates. Variations in the pore water velocity were sufficient to account for the observed dispersion without requiring a dispersion term. Agreement between modelled and predicted profiles in the second experiment was not as good, with the model under estimating the degree of spreading of the solute, especially at early times. Variations in the infiltration properties alone did not account for the observed field-scale solute dispersion. Failure to predict the solute movement through this soil may be due to inadequacies in estimating the effect of evaporation on the distribution of effective infiltration.

Based on the results of these two field tests, the stream-column model shows promise for modeling field-scale solute transport. In addition, the method described for estimating the model parameters independent of the leaching experiments shows promise in transforming the model into a fully predictive model. The model can be easily expanded to include adsorption - desorption reactions and solute degradation. However, difficulties still remain in estimating the mobile water content for a given soil and solute and in accounting for evaporation in the variance of the effective infiltration.

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PERSONNEL

D. B. Jaynes, R. C. Rice, and R. S. Bowman

Table 1. Cumulative infiltration, cumulative effective infiltration, calculated mean pore water velocity, and the mean of the log-transformed pore water velocity for the two leaching sites.

date	$\sum\mu_I$	$\sum\mu_{I_e}$	m_v	$\mu_{\ln v}$
(d)	(mm)	(mm)	(mm/d)	(-)
		Experiment 1 - sandy loam		
5	100.	67.	18.5	2.72
25	100.	67.	3.70	1.11
47	150.	102.	3.22	0.973
68	200.	122.	2.70	0.797
96	250.	128.	2.02	0.507
126	350.	132.	1.59	0.267
		Experiment 2 - sand		
12	78.	65.	6.32	1.82
18	78.	65.	4.22	1.42
25	178.	113.	4.97	1.58
32	254.	171.	5.61	1.70
40	320.	211.	5.43	1.67
49	394.	251.	5.20	1.63

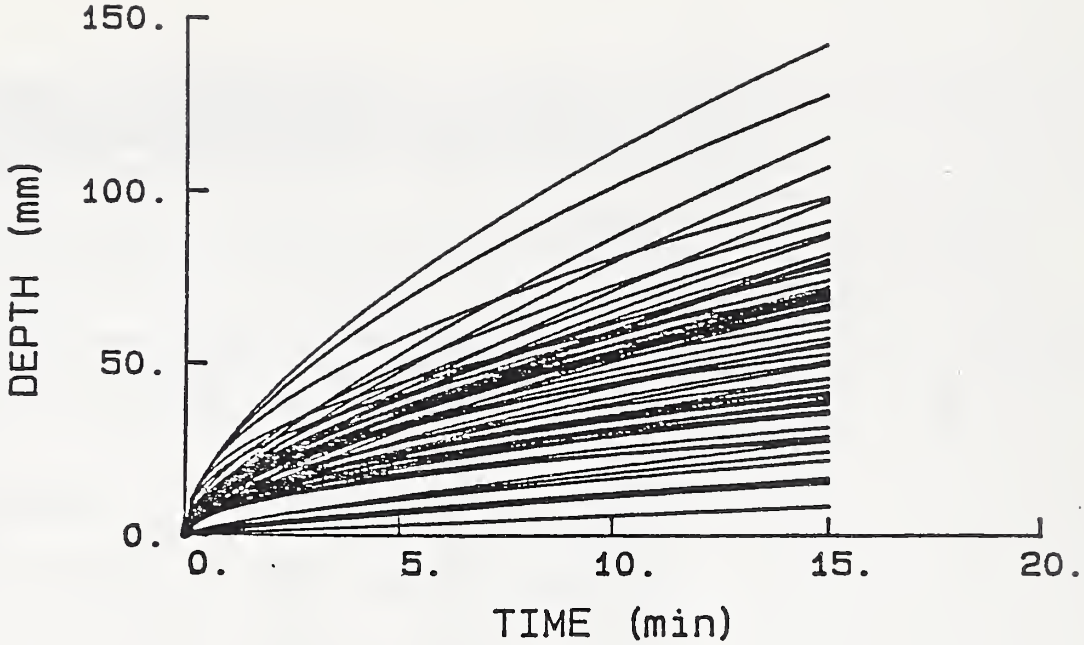

Figure 1. Infiltration depths versus time measured with 63 infiltrometers at sandy loam site.

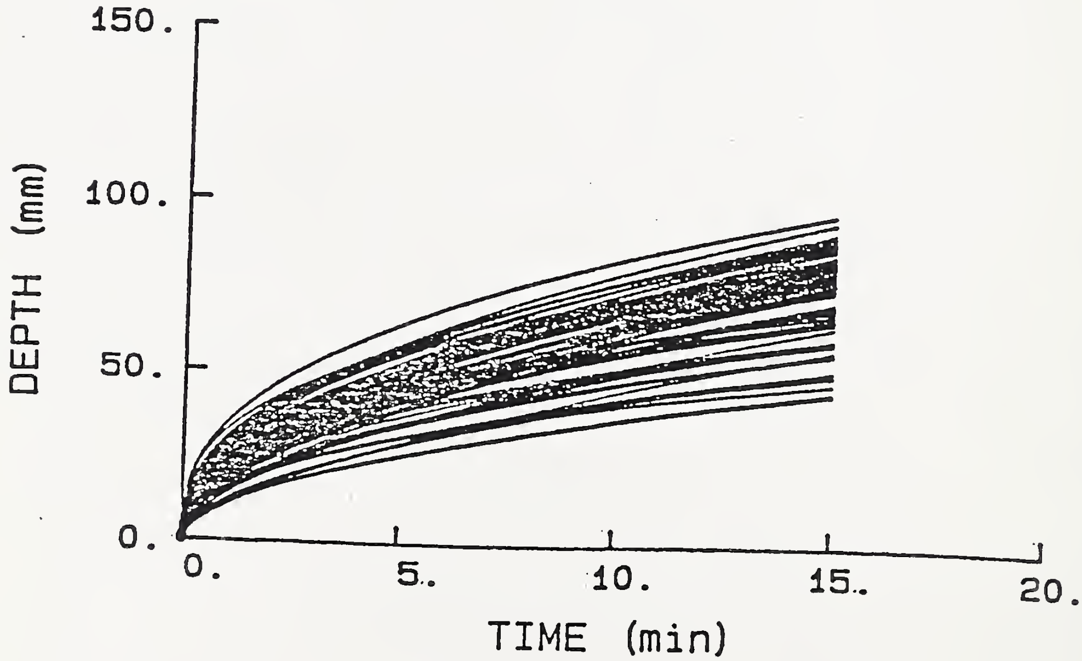

Figure 2. Infiltration depths versus time measured with 71 infiltrometers at sand site.

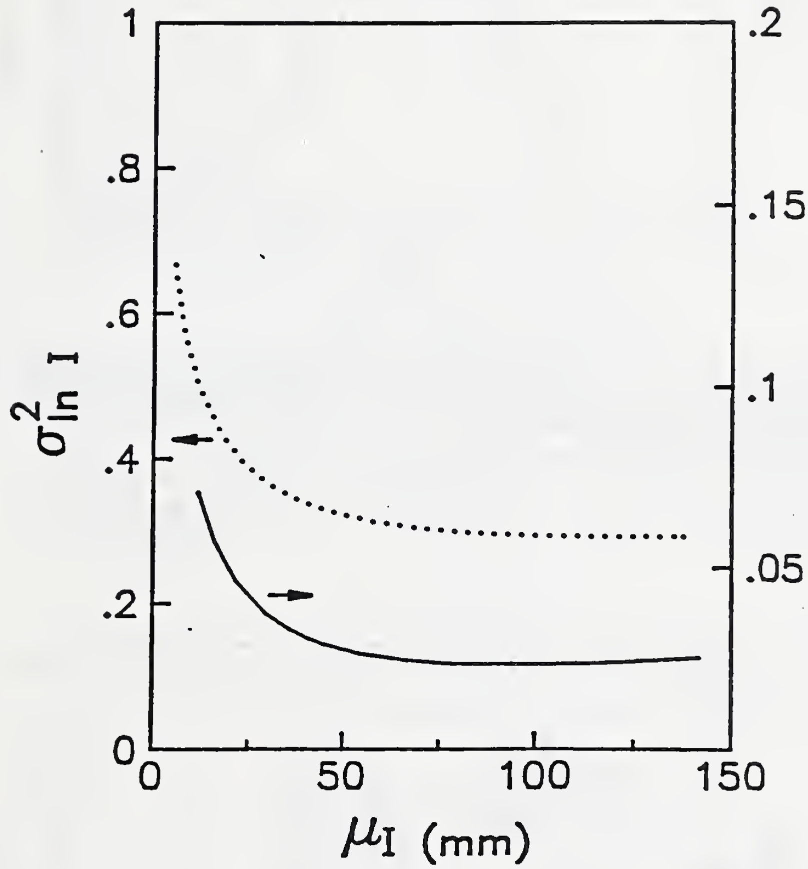

Figure 3. Dependence of variance on irrigation depth. Results for sandy loam (dotted line) and sand (solid line).

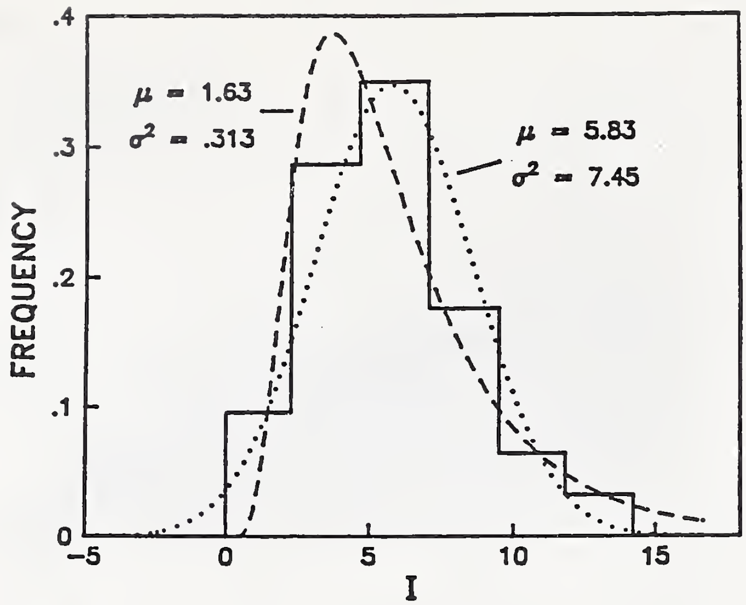

Figure 4. Histogram of I values after 15 minutes of infiltration on sandy loam and corresponding normal (broken line) and log-normal (dotted line) distributions.

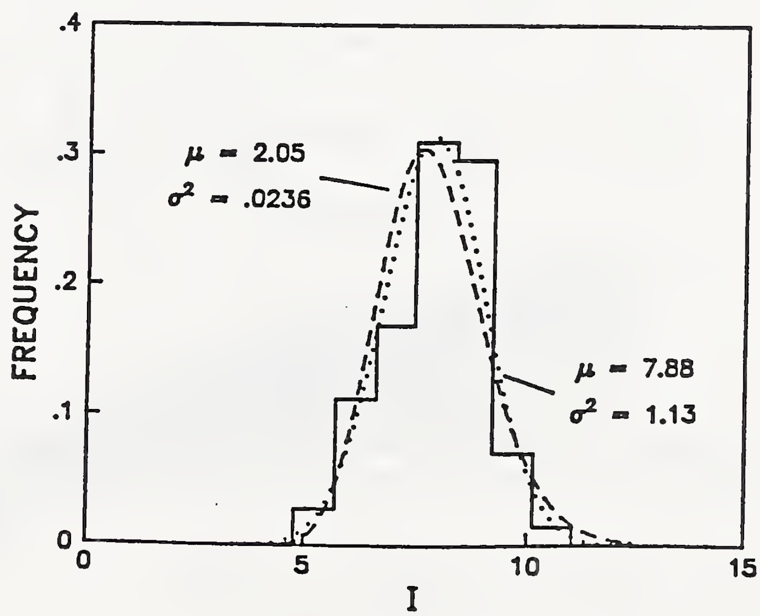

Figure 5. Same as Fig. 4 for sand soil.

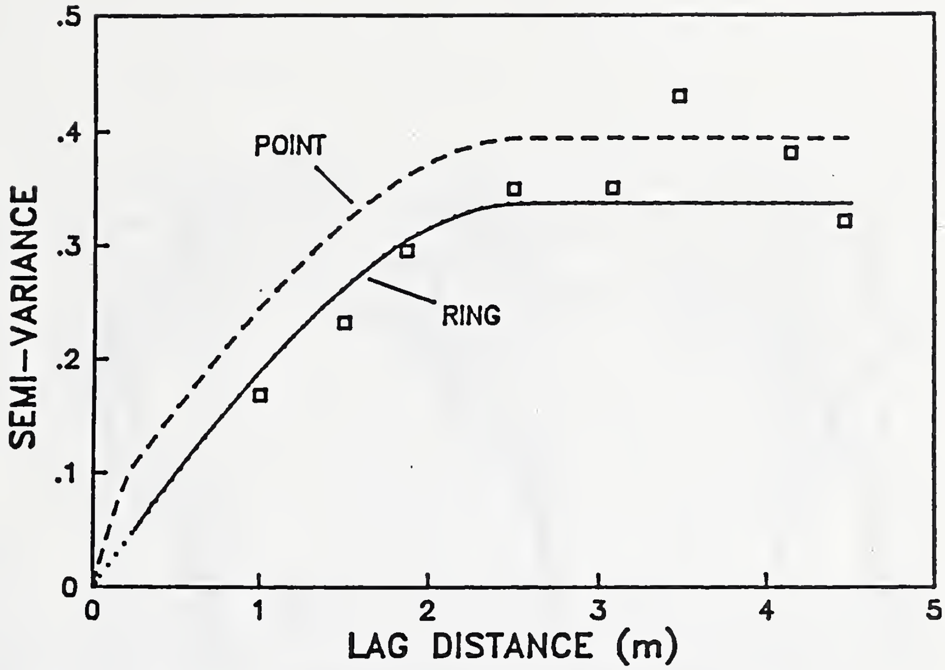

Figure 6. Experimental (points) and theoretical (solid line) semi-variograms for the sandy loam ln I data based on the ring diameter support. Dashed line is the deregularized point semi-variogram, while the dotted line is the semi-variogram calculated from the point support regularized to the ring support.

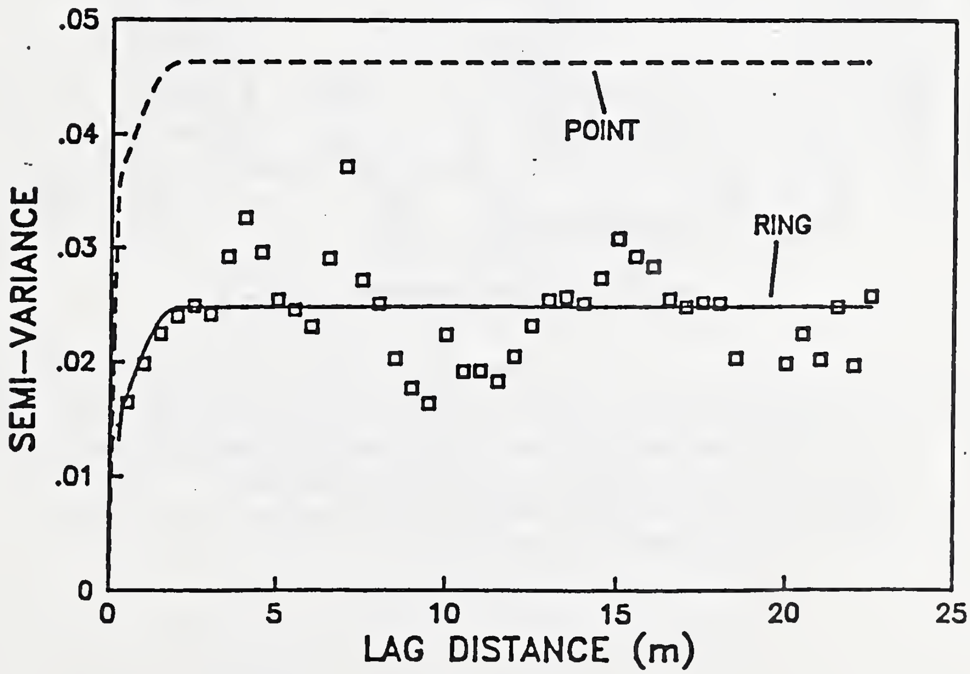

Figure 7. Same as Fig. 6 for the sand data.

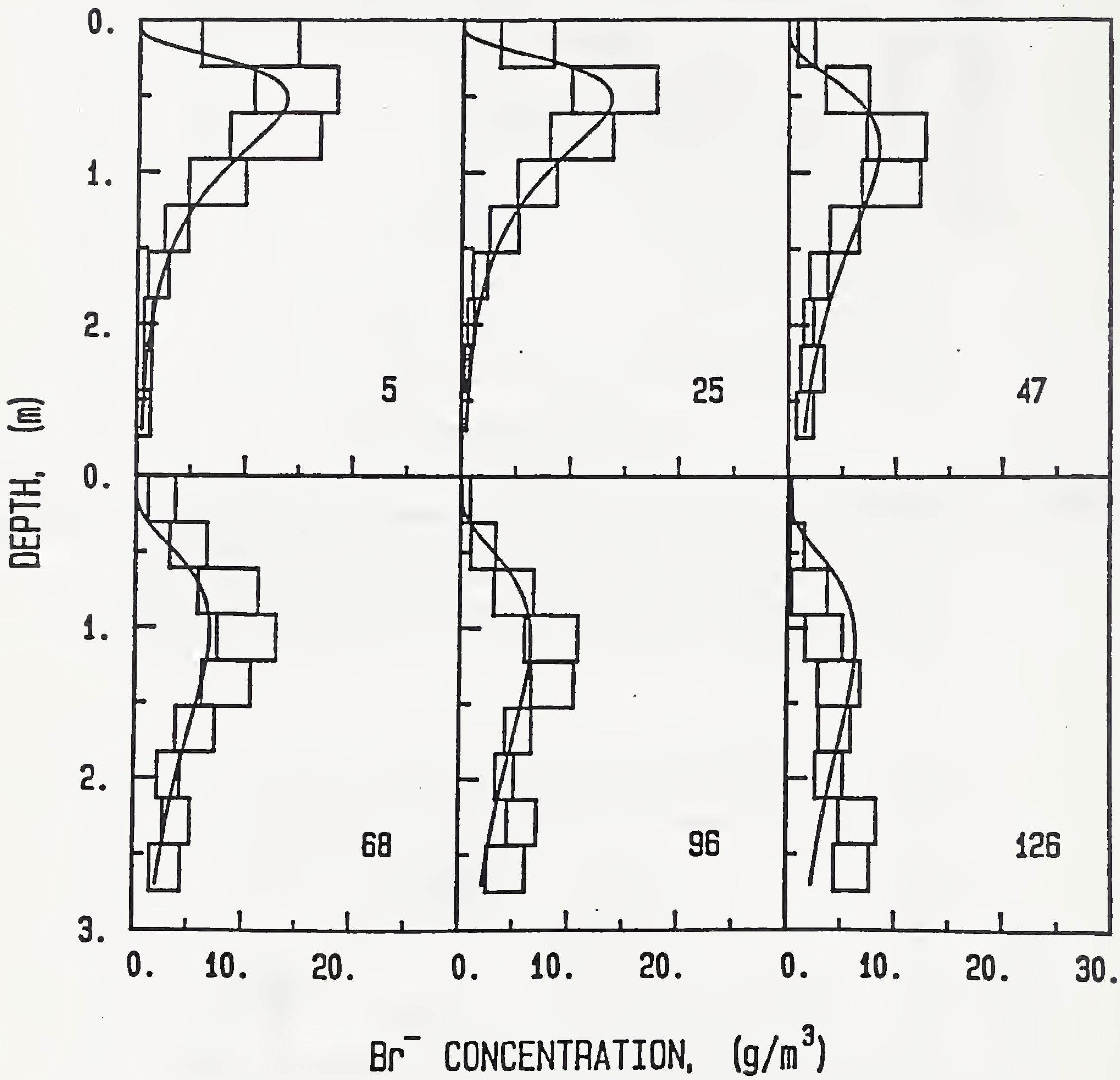

Figure 8. Br$^-$ concentrations versus depth for six sampling dates (figure labels) at the sandy loam site. Rectangles enclose the 95% confidence limits for the measured mean concentration for each measured increment. The smooth curves are the model predictions.

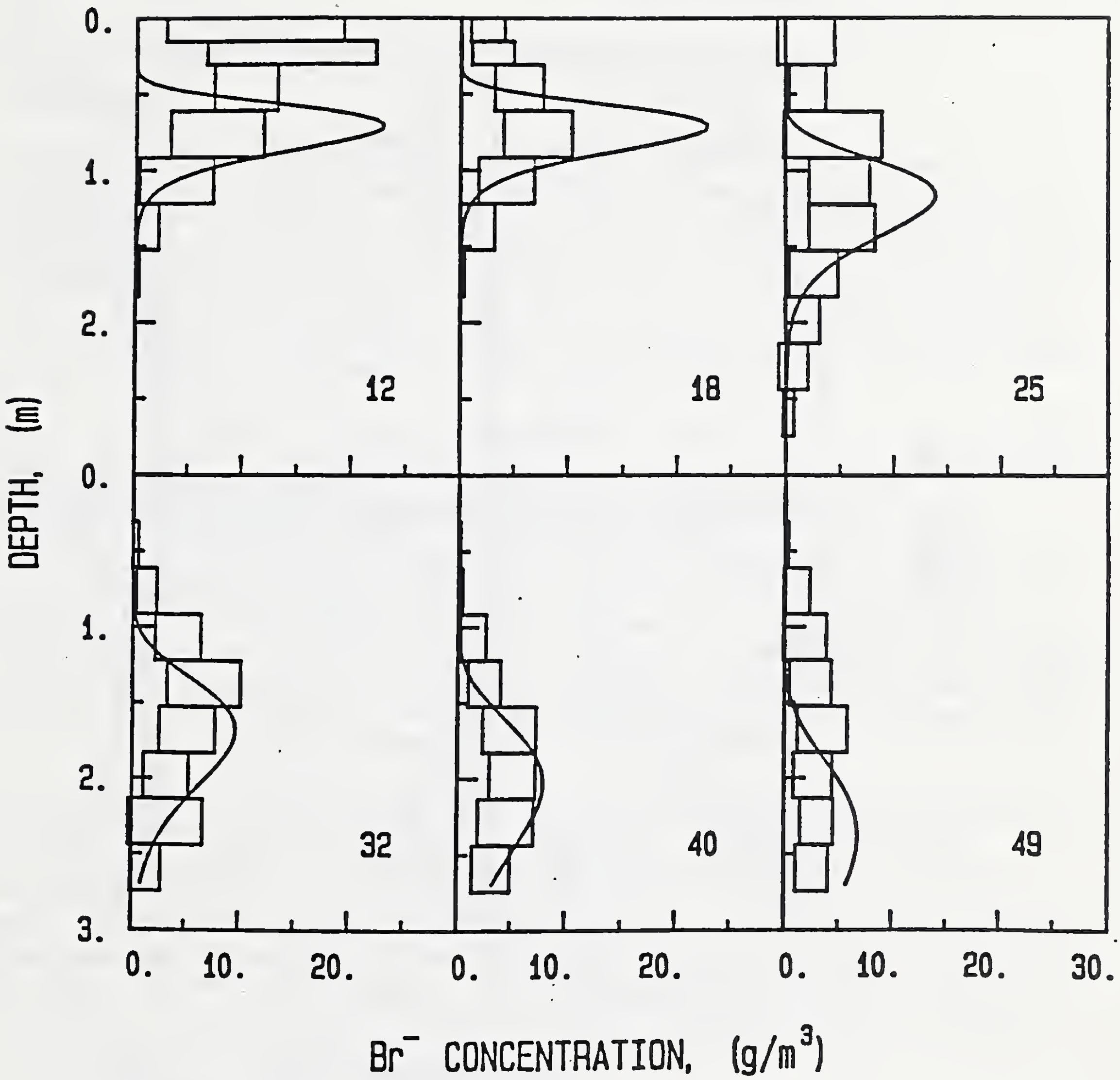

Figure 9. Same as Fig. 8 for the sand.

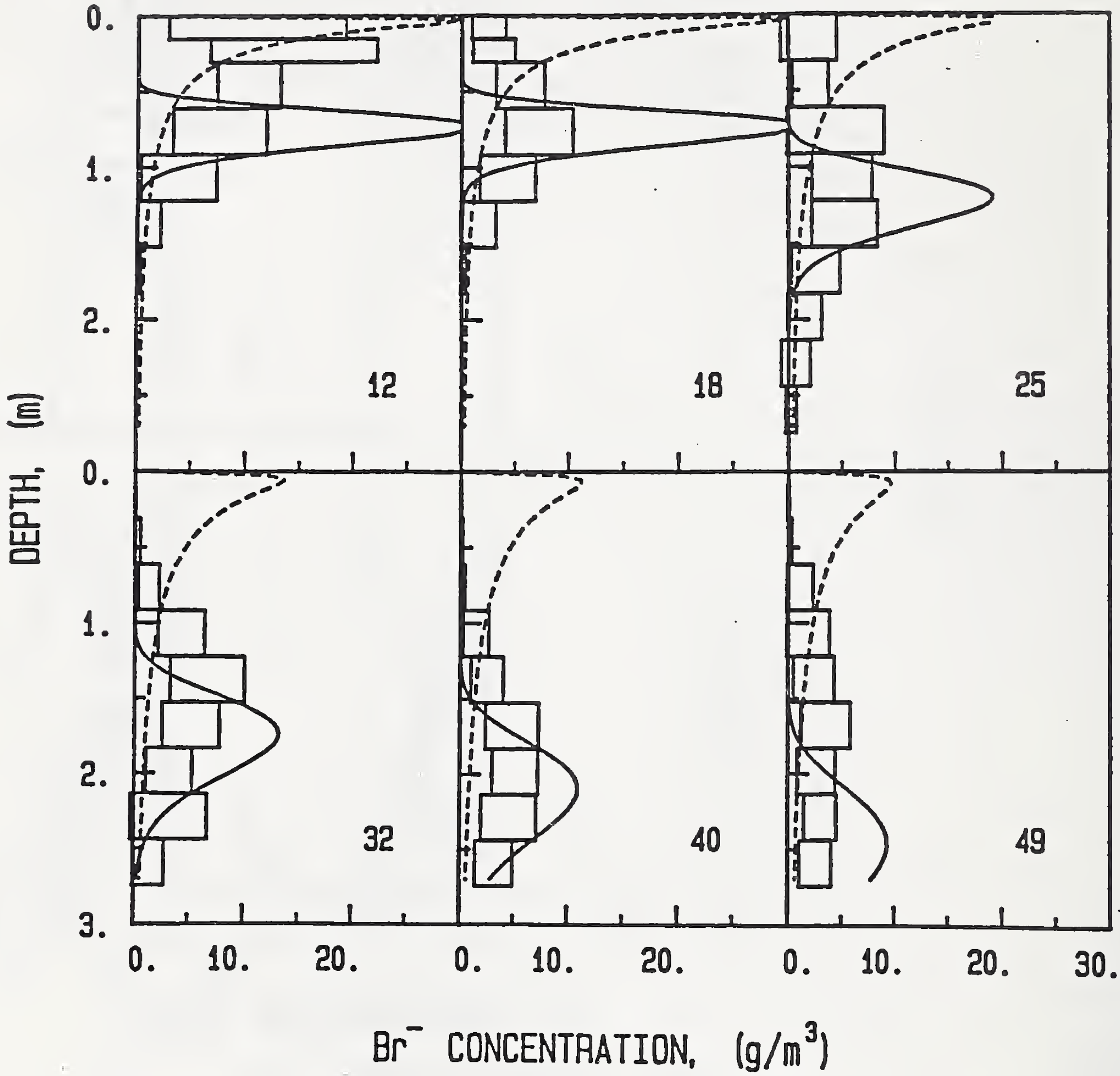

Figure 10. Same as Fig. 8 for the sand where the model prediction uses either the measured $\sigma^2_{\ln I}$ directly for an estimate of $\sigma^2_{\ln V}$ (solid line) or a corrected estimate based on assumption of independent measurements (broken line).

TITLE: Spatial and Temporal Variability of Water Content and Infiltration on a Flood Irrigated Field[1]

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-11130-003

INTRODUCTION

Much of the non-uniformity in irrigation is caused by the spatial variability in soil hydraulic properties. If we can characterize and quantify this variability, we can make use of this information to design better irrigation systems and estimate the uniformity of irrigation and its effect on crop yields and deep percolation. In a flood-irrigated border, we measured the water content at 44 locations before and after four irrigations. In addition, infiltration rates were measured within 42 single-ring infiltrometers during each irrigation.

Water content data documented considerable variability in water storage across the field. Spatial correlations of water storage before and after irrigation were found to extend up to distances of 30 m by variogram analysis (Fig. 1). The spatial pattern of water storage appears to be stable over time as indicated by identical variograms for each irrigation and rank correlation tests. This stability over a growing season may reflect the distributions of soil texture and bulk density across the field. Irrigation depths, as calculated from changes in water storage, were more variable over time but were also spatially correlated as indicated by variogram analysis (Fig. 2), although there was a larger random component to their variability.

Spatial structure implies that the distribution of water storage can be quantified with fewer measurements than if storage were a random function of position. Temporal stability implies that only a few measurements need be taken to characterize an entire field once the spatial distribution of water storage is known. The initial measurement of the spatial distribution still remains a problem considering the time and expense required for making water content measurements. However, correlations between water content and soil texture and bulk density or other easily measured field properties may facilitate these measurements.

Irrigation depths measured with 0.25-m ring infiltrometers also showed considerable variability, with coefficients of variability as high as 53%. Infiltration depths corresponding to the opportunity time of each irrigation were highly correlated between irrigations indicating a high degree of temporal stability in infiltration (Table 2). Kostiakov's equation was fit to the data from each infiltrometer. The resulting regression parameters were inversely correlated to each other but surprisingly showed little correlation between irrigations when considering the high correlations of infiltration depths. No spatial structure was found for the infiltration depths beyond the minimum infiltrometer spacing of 3.8 m.

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[1] Presented as ASAE Paper No. 88-2584.

Infiltration variability within infiltrometers was very large within this border, while the mean depth infiltrated within all of the infiltrometers during an irrigation was considerably less than for the border (Table 1). The infiltrometer data illustrates the difficulties in determining infiltration equation parameters that are representative of field infiltration processes. Infiltrometers may be better suited for measuring the surface infiltration variability, but since they ignore lateral redistribution, they underestimate the uniformity in water storage seen by an established root system.

PERSONNEL

D. B. Jaynes and D. J. Hunsaker

Table 1. Comparison of irrigation uniformity calculations for four irrigations made from measured input volume and border area, water content measurements at 44 locations, and 42 infiltrometers.

Day of	supply ditch weir			neutron probe			ring infiltrometer		
Year	μ	σ	CV	μ	σ	CV	μ	σ	CV
	(mm)	(mm)		(mm)	(mm)		(mm)	(mm)	
80	134	---	--	133.9	20.8	16	83.3	43.8	53
99	105	---	--	89.6	21.2	24	62.3	30.2	48
108	98	---	--	92.7	17.3	16	61.6	30.5	50
127	104	---	--	91.9	17.3	19	65.6	29.3	45

Table 2. Means, variances, and correlations for infiltration parameters and depths calculated from infiltrometer measurements made during four irrigations. Also correlations with the bulk density, ρ, and percent clay, and sand for the surface soil within the infiltrometers are given. Rank correlations for infiltration depths are shown in lower left half of correlation table.

Irrigation		Mean	Variance	Irrigation 1 I	Irrigation 1 s	Irrigation 1 b	Irrigation 2 I	Irrigation 2 s	Irrigation 2 b	Irrigation 3 I	Irrigation 3 s	Irrigation 3 b	Irrigation 4 I	Irrigation 4 s	Irrigation 4 b	ρ	% clay	% silt	% sand
1	I(mm)	83.3	1920		-.133	.531**	.811**	.063	.083	.751**	.201	.045	.788**	.036	.288	-.543**	-.123	-.116	.226
	$s(mm/s^b)$	.190	.0243			-.777**	.142	.157	-.268	.052	-.059	.146	.035	.185	-.153	.070	-.253	.118	.169
	b	.578	.0090				.282	-.086	.310*	.402*	-.035	.153	.393*	-.088	.276	-.234	-.036	-.103	.124
2	I(mm)	62.3	911	.728**				.009	.240	.896**	.026	.251	.877**	.064	.294	-.460**	-.216	-.252	.423**
	$s(mm/s^b)$	.118	.0222						-.730**	.220	.008	.022	.087	.424**	-.286	-.173	-.381*	.360*	.100
	b	.623	.0156							.102	.027	.118	.126	-.387*	.374*	-.183	.171	-.333*	.093
3	I(mm)	61.6	928	.745**			.861**				.021	.337*	.935**	.071	.309	-.536**	-.313*	-.099	.398**
	$s(mm/s^b)$	.255	.0742									-.780**	.002	-.094	.025	-.253	.145	.044	-.183
	b	.525	.0095										.281	.068	.154	-.032	-.416**	.017	.409*
4	I(mm)	65.6	857	.794**			.815**			.906**				-.070	.441**	-.528**	-.234	-.141	.361*
	$s(mm/s^b)$	.320	.0669												-.828**	-.132	-.205	.348*	-.070
	b	.506	.0097													-.164	.089	-.280	.137
	ρ (kg/m^3)	1620	4600														.078	-.161	.052
	% clay	17.2	5.72															-.459**	-.674**
	% silt	24.1	3.55																-.348
	% sand	58.7	5.14																

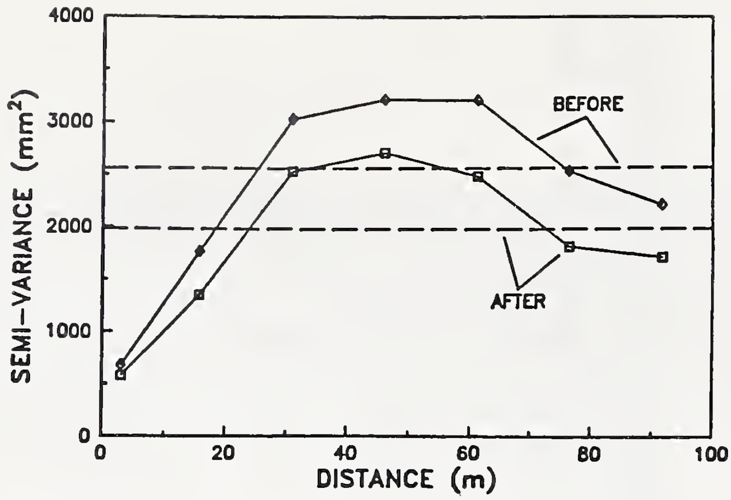

Figure 1. Combined experimental variograms for water storage before and after irrigation (solid lines). Dashed lines are the average variances for the four irrigations.

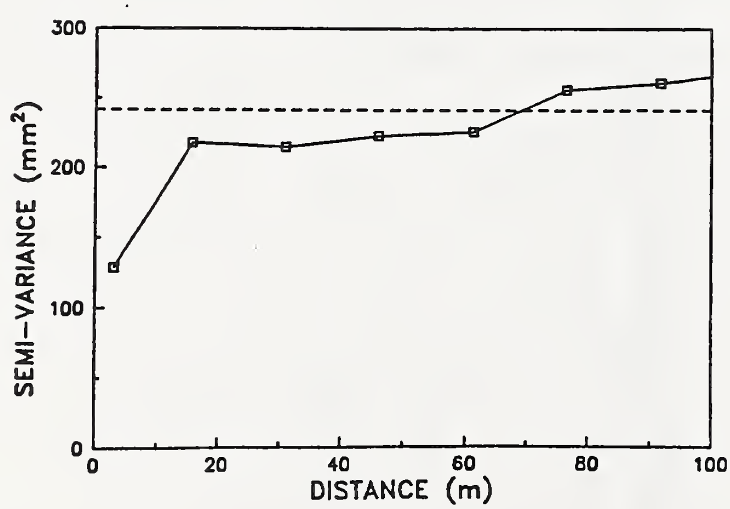

Figure 2. Combined experimental variogram for the change in water storage due to irrigation (solid line). Dashed line is the average variance for the four irrigations.

TITLE: Factors Affecting Separation of Organic and Inorganic Soil Tracer Anions via Strong-Anion Exchange (SAX) HPLC Column.

SPC: 1.3.02.1.a
1.1.02.1.c

CRIS WORK UNIT: 5344-11130-003

INTRODUCTION

In order to trace groundwater movement in soil, anionic compounds have been used due to little or no retardation of flow caused by interaction with soil particles and stability to degradation. As analytical assay methods improved from selective-ion electrodes and colorimetric to chromatographic methods, the range of application of anionic soil tracers became a broader and more important tool for detecting ground-water movement and percolation. The organic tracer anions which meet these requirements are 2,6-difluorobenzoate (2,6-DF), o-trifluoromethylbenzoate (o-TFMBA), m-trifluoromethyl benzoate (m-TFMBA), and pentafluorobenzoate (PFBA). The inorganic anionic tracers usually used are rare elements or compounds in the natural soil condition such as bromide (Br^-), iodide (I^-), and thiocyanide (SCN^-). However, iodide and thiocyanide were proven somewhat less stable than the other listed compounds.

Cortes (1981) could avoid high background interference in HPLC from natural chloride and sulfate on an amine bonded phase silica column by detecting at 205 nm. Stetzenbach and Thompson (1983) developed an ion-exchange HPLC method on a Partisil SAX-10 μm column (Whatman, Clifton, NJ, U.S.A.)[1], which is superior to colorimetric and ion-selective methods for determination of chloride, bromide, nitrate, thiocyanide and iodide ions in groundwater. Reeve (1979) analyzed inorganic ions in the nanogram detection range of anionic tracers in combination with an ion-pairing reagent and cyano column detection at 205 nm. With similar methods, Thayer and Huffaker (1980) used HPLC with UV detection at 210 nm to determine nitrate and nitrite in biological samples. Bowman (1984) illustrated an HPLC analysis method for the listed organic and inorganic anionic soil tracers plus naturally occurring nitrate and nitrite, by using different brands of strong-anion exchange columns (Regis, Morton Grove, IL, U.S.A., and Whatman SAX 10 μm). The mobile phase was 5 mM potassium phosphate buffer at pH 4.0 and 10 % aceto-nitrile. The reproducibility of the chromatography was excellent if the analysis was run continuously within 2 to 3 days. However, if the analysis period was longer than 2 to 3 days or was discontinued and the HPLC system left idling with 0.1 mℓ/min of the mobile phase flow for several days, it required modification of either lowering the pH of the buffer or increasing the pumping rate of acetonitrile (ACN), or both parameters simultaneously to obtain better resolution of the peaks. Also, even slight modification of the solute concentration or the pH of the buffer or acetonitrile ratio in the mobile phase resulted in shifting of retention times and elution sequences of the listed com-

[1]Mention of company and trade names is for the convenience of the reader and does not imply any preferential treatment or endorsement by the U. S. Department of Agriculture.

pounds. For this reason, this experiment was conducted to elucidate the mechanism of the peak shifting and seek the best chromatography methods to increase resolution of individual compounds and minimize co-elution problems with other contaminates.

MATERIALS AND METHODS

Chromatography: All the components were from the Waters HPLC system (Waters Assoc. (Milford, MA, U.S.A.). The solvent delivery system consisted of Model 6000A and Model 501 pumps. The injector used was Model U6K syringe injector, and the detector was Model 490 set at 205 nm and 0.3 absorbance unit full scale (AUF). Baseline 810, computer software program, was used for hardware control and data processing. Chromatography was carried out at ambient temperature on 25 cm x 4.6 mm (i.d.) Regis Hi-Chrome Reversible Strong Anion Exchange column (SAX) and 1 cm x 3 mm guard cartridge column. To evaluate effects of pH and solute concentration in the buffer, and acetonitrile content in the mobile phase on separation of anionic soil tracers, 100 chromatographs were made by combining 5 levels of pH (2.5, 2.8, 3.1, 3.4 and 4.6), 4 levels of solute concentrations (10, 15, 20 and 30 mM), and 5 levels of ACN rates in the mobile phase (30, 40, 50, 60, and 70%). The flow rate of the mobile phase was 2 mℓ/min. The sample was prepared with 10 ppm of each compound and 25 $\mu\ell$ was injected.

Chemicals: 2,6-DFBA, PFBA and o-TFMBA were obtained from Aldrich (Milwaukee, WI, U.S.A). m-TFMBA was obtained from PCR Research Chemicals (Gainesville, FL, U.S.A). Each of these compounds had a purity in the range of 97-99% according to the manufacturer.

RESULTS AND DISCUSSION

Due to characteristic ion strength and polarity of individual compounds, the retention time varied tremendously with minor modification of the pH, solute concentration, and ACN ratio in the mobile phase. Increasing solute concentration resulted mainly in faster elution of the compounds with the least change in the relative retention time as compared to modification of other parameters such as pH and ACN ratio in the mobile phase as shown in Figure 1. The same trend was observed in the fingerprints of identical pH and ACN but different solute concentrations (10 and 30 mM of potassium phosphate), as shown in Figures 2 and 3.

When the pH of the mobile phase was changed, the compounds had higher pKa values; thus a higher degree of fluctuation in the relative retention time and extra peaks were detected in some cases as shown in Figures 2 and 3. Hence, the cause of the shift in relative retention time was speculated to be due to the change in ionic strength and polarity under different pH's. Since it had the lowest pKa, the relative retention time of the nitrate ion was less affected by the pH of the mobile phase.

The effect of different ACN ratios in the mobile phase on relative retention times was great enough to shift the elution sequence of the eight standard compounds as shown in Figure 4. The retention times of the organic tracers were much more sensitive than those of the inorganic

tracers; however, the relative retention time for iodide was considerably higher despite iodide being an inorganic anion.

Since a soil extract contains various organic compounds, in running isocratic chromatography, co-elution problems were frequently encountered. One effective method of avoiding this problem is the application of the gradient method starting with a lower ACN ratio (15-20%) in the mobile phase followed by an increase to 70-85% depending on the situation of the chromatograph shown in Figure 5.

PFBA reacted with ACN, thus producing a non-ionic and lower polarity compound as a function of time. The rate seemed to indicate first-order reaction; the reaction resulted in extra peaks in the chromatogram. However, reaction rate was not determined.

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PERSONNEL

H. Cho, E. M. Cioto, and C. S. Souther

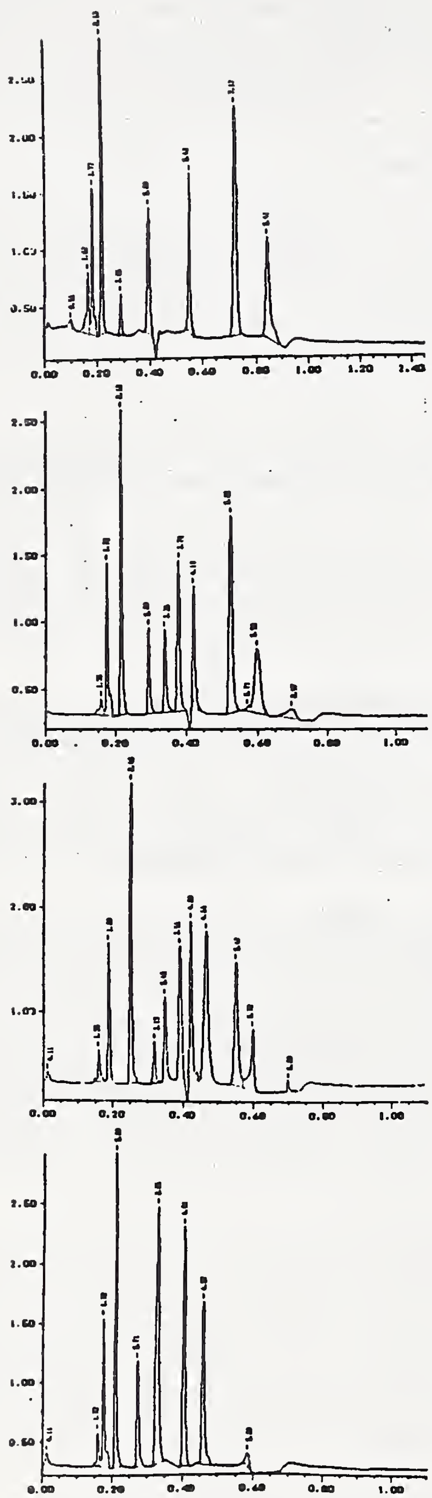

Figure 1. Chromatograms of 2,6-DFBA, o-TFMBA, m-TFMBA, PFBA, KBr, KNO_2, KNO_3, and KI at 5 ppm with 5 u Regis SAX column. The mobile phases were 70% acetonitrile and 10, 15, 20, and 30 mM of potassium phosphate buffer at pH 2.8.

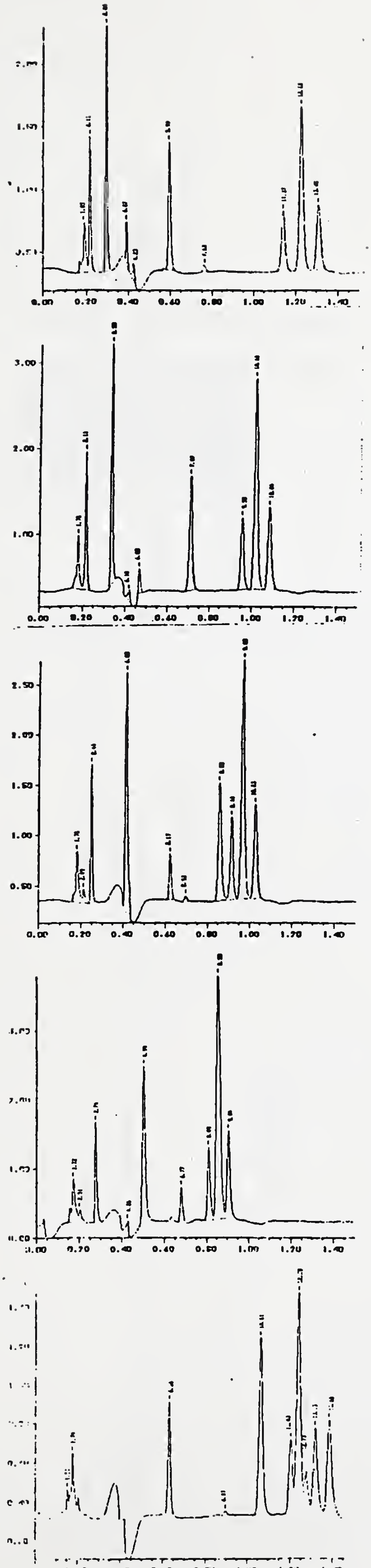

Figure 2. Chromatograms of 2,6-DFBA, o-TFMBA, m-TFMBA, PFBA, KBr, KNO_2, KNO_3, and KI at 5 ppm with Regis 5 u SAX column. The mobile phases were 50% acetonitrile and 10 mM of potassium phosphate buffer at pH 2.5, 2.8, 3.1, 3.4, and 4.6.

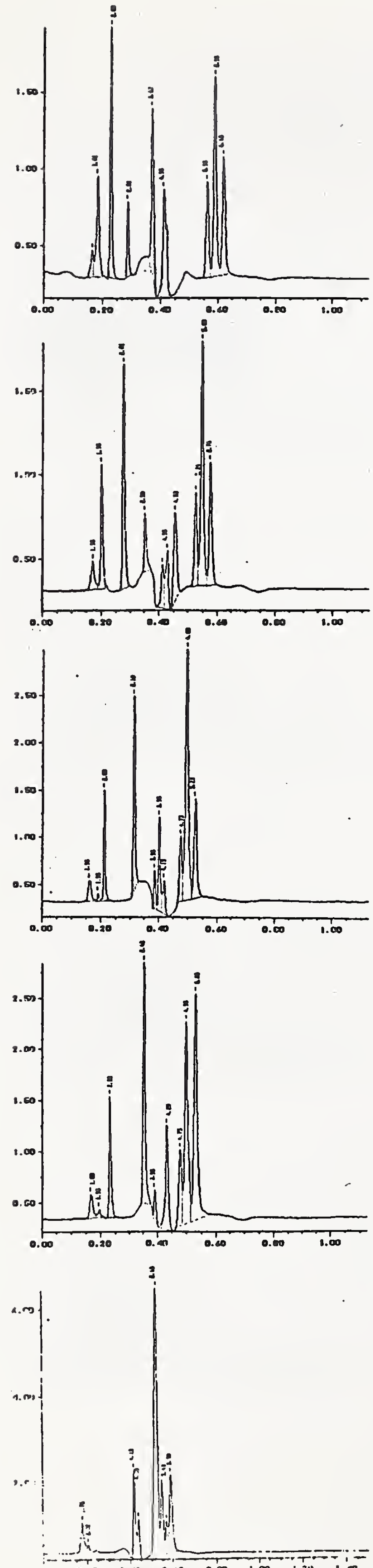

Figure 3. Chromatograms of 2,6-DFBA, o-TFMBA, m-TFMBA, PFBA, KBr, KNO_2, KNO_3, and KI at 5 ppm with 5 u Regis SAX column. The mobile phases were 50% acetonitrile and 30 mM of potassium phosphate buffer at pH 2.5, 2.8, 3.1, 3.4, and 4.6.

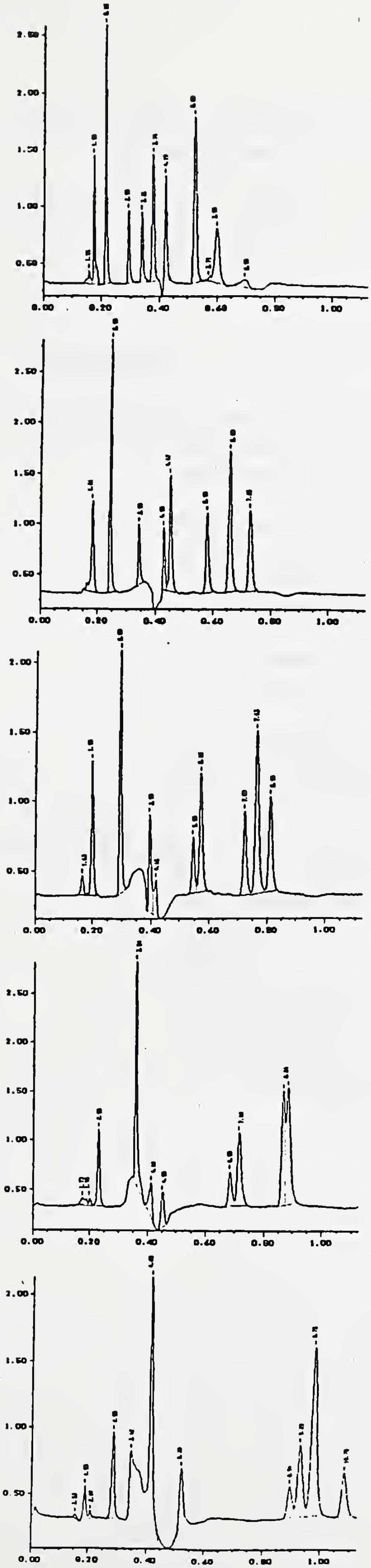

Figure 4. Chromatograms of 2,6-DFBA, o-TFMBA, m-TFMBA, PFBA, KBr, KNO_2, $KNOO_3$, and KI at 5 ppm with 5 u Regis SAX column. The mobile phases were 15 mM of potassium buffer at pH 2.8 and 70, 60, 50, 40, and 30% of acetonitrile.

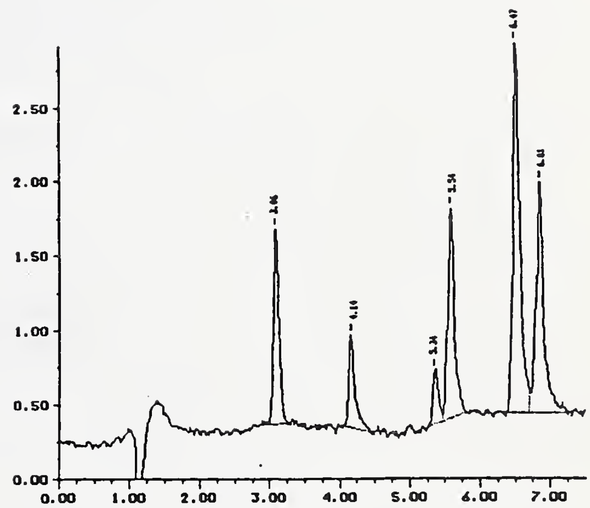

Figure 5. Gradient chromatograms of 2,6-DFBA, m-TFMBA, PFBA, KBr, KNO_3 at 5 ppm with Regis SAX column. The mobile phases consisted of 15 mM potassium buffer at pH 2.5 and a gradient of acetonitrile was 15% until 3 min, then ramped up to 75% during 1 min and remained 75% for 5 minutes.

TITLE: PREDICTING EFFECTS OF INCREASING ATMOSPHERIC CO_2 AND CLIMATE CHANGE ON YIELD AND WATER USE OF CROPS

SPC: 1.3.01.1.b 050%
1.1.03.1.d 050%

CRIS WORK UNIT: 5344-11130-004

OUTLINE

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INTRODUCTION

The CO_2 concentration of the Earth's atmosphere has been rising steadily since the inception of the Industrial Revolution. It is expected to continue to rise for the next several centuries with a doubling projected to occur in perhaps 60 years around the middle of the 21st century. To determine what the CO_2 increase portends for agriculture, researchers at the U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory conducted several comprehensive CO_2-enrichment experiments from 1983 through 1987 using the open-top chamber approach (Kimball et al., 1983, 1984, 1985, 1986, 1987). These studies provided much valuable information about the effects of elevated CO_2 on the growth, yield, physiological processes, and water use of cotton. CO_2-enrichment produced large increases in cotton yield. Other species were also studied including water hyacinth, azolla, carrot and radish. A strong positive temperature interaction was observed which could be important in view of the predicted increases in global temperature concomitant with the increase in CO_2 concentration. In other laboratory studies, cotton grown at high CO_2 was found to retard the growth and development of beet armyworm larvae.

Following these experiments, additional research activities were started during 1988 that are logical extensions of the prior work. As will be described in this report, these activities included: (1) investigation of the effects of high-CO_2-grown cotton on beet armyworm growth, both of individual larvae in the laboratory and of whole populations in "screen-top" chambers in the field; (2) evaluation of the long-term effects of elevated CO_2 on the growth of orange trees, as well as of agave and sorghum in the same open-top chambers as the orange trees while they are small; (3) determination of the effects of carbonated irrigation water (FIZZ) and of a free-air CO_2 enrichment (FACE) on cotton growth and yield, which actually is the third year of this experiment; (4) development of a cotton growth model for predicting effects of increasing CO_2 and climate change on yield and water use; and (5) creation of a computerized data base of quantitative information extracted from the literature about the effects of CO_2 enrichment on growth, yield, and other physiological processes of plants.

BEET ARMYWORM GROWTH ON HIGH-CO_2-GROWN HOST COTTON

A. Laboratory Experiment - Beet armyworm development and temperature interactions.

Growth, developmental time, and survival of the beet armyworm (BAW), *Spodotera exigua* (Hubner) were studied. Deltapine 61 cotton seedlings were grown in two greenhouses (30°C day, 24°C night). One greenhouse was maintained at a CO_2 level of 650 μmol mol^{-1} and the other at an ambient CO_2 level of 325 μmol mol^{-1}. Hoagland solution (75 ml) was used to fertilize the seedlings every other day after the 1st-two true leaves appeared.

To date, tests have been conducted in 4 incubators held at 24, 27, and 30° °C with an 18:6 L:D photoperiod. Air was ducted to 2 of the incubators from the CO_2 enriched greenhouse and to the other 2 from the ambient greenhouse. Eight seedlings were kept in each incubator at a time. One--three newborn BAW larvae were placed on each cotton seedling (at 1st-2 true leaves). Containment was by clear plastic cages that enclosed each seedling from the stem upward. Seedlings were replaced as needed as the growing larvae defoliated them. BAW were collected when mature larvae entered the "wandering" (prepupal) stage or pupate. Pupae were weighed and sexed.

Upon completion of the last temperature regime (21 °C), data will be summarized and analyzed by analysis of variance to determine BAW growth, developmental time, and survival. Measurements of leaf area and leaf area eaten have proven difficult to obtain at the accuracy needed for determination of nutritional indices. To overcome this problem, a new leaf area method will be tried by using a digital image analysis system which has been ordered but has not yet arrived. C:N ratios have been determined for the cotton seedlings grown at the 3 temperatures investigated this year; ratios have also been determined for the population experiment described in part B (Field Experiment) of this report (see Akey et al., 1988, and Kimball et al. 1987, for methods). Determinations of wet and dry leaf weights and BAW frass weights will be made for replicates at all temperatures once accurate leaf area measurements are obtained. This will permit nutritional indices to be determined.

B. Field Experiment - Population Dynamics in CO_2-enriched Screen-top Chambers

The enhanced carbohydrate under CO_2 enrichment increases the carbon: nitrogen ratios in some plant tissues (Oechel & Strain 1985). This tends to decrease the nutritive quality of those tissues. Also, little is known at this time about whether elevated CO_2 will induce any changes in secondary-plant compounds that affect insect behavior and physiology. CO_2-related changes may alter the damage done by herbivorous insects. Data are needed to assess this problem and plan for future insect control under these conditions.

To date, the only study on the effects of CO_2-enriched cotton on insect populations has been on the sweet-potato whitefly, Bemisia tabaci (Gennadius) (Butler et al. 1986). They observed no differences between population levels on CO_2-enriched cotton and ambient cotton. However, the white fly is a phloem feeder (Pollard 1955) and the C:N ratio of the phloem was probably not affected. In contrast, beet armyworms (BAW), as foliage feeders, are directly dependent on foliage quality and our recent work (Akey and Kimball 1989) showed that its growth, development time, and survival were adversely affected when raised on CO_2 enriched

cotton plants. However, regardless of effects of CO_2 enriched host plants on individuals, it is the effects of insect populations on those plants that concern us most.

1. Culture of the cotton crop.

The cotton crop was grown in the field just west of the Western Cotton Research Laboratory, Phoenix, Arizona, where the 1984-1987 experiments were conducted (Kimball et al. 1984, 1985, 1986, 1987). A plot plan is shown in Fig. 1. The soil is Avondale clay loam (Fine-loamy, mixed (calcareous), hyperthermic, Anthropic Torrifluvent). Following the 1987 experiment, all equipment was removed from the field, and it was tilled and planted to a winter crop of barley. There were visible differences in barley growth resulting from the different CO_2, water, and nitrogen treatments of the 1987 experiment. In March the field was disked, and the barley residue was incorporated into the soil in an effort to mask the soil differences.

In early April the field was plowed into ridges and furrows. A preplant herbicide Prowl[1] (pendimethal) was applied at a rate of 1.5 pint per acre, and ammonium sulfate-phosphate (16-20-0, 26.9 kg N/ha, 14.8 kg P/ha) was broadcast. Using a two row planter, cotton (Deltapine-77) was planted on 28 April 1988 with a row spacing of 1.016 m (40 in.), and then the field was irrigated by flooding (Table 1). About half the cotton was emerged by 6 May, and on 16 May the population was thinned to 10 plants/m (100,000 plants/ha) over the field, but the actual resultant plant numbers in the chambers were about 40 (40 plants/3 m of row = 133,000 plants/ha).

As described in more detail in the next section, chamber construction commenced on 9 May and, except for the screen-tops, was mostly completed by 17 May, when a second flood irrigation was applied. The CO_2 treatments to the enriched chambers started on 19 May. Another flood irrigation was applied on 1 June, but after that water was applied daily via a drip irrigation system (Table 1). As in previous years (Kimball et al., 1985, 1986, 1987), the amount of water to apply was determined from the pan evaporation amount of the week before (times 1/3 the leaf area index) with corrections for rain and for over- or under-irrigations the previous week. The amount of time per day that the irrigation system operated was adjusted weekly. The screen-tops were installed on the chambers beginning on 9 June, followed by the vestibules.

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[1] Trade and company names are mentioned for the benefit of the reader and do not imply preferential treatment or endorsement of the products listed by the U.S. Department of Agriculture.

Nitrogen fertilizer was injected into the drip irrigation water (Table 2), with the applications (including preplant) totaling 247 kg/ha. Cotton leaf petioles were sampled from the chambers on 3 days during the season and analyzed for NO_3^--nitrogen. These data are presented in Table 3, where it can be seen that the N levels tended to be low possibly because of the barley cover crop and in spite of the fairly liberal application of fertilizer. As observed previously (Kimball et al., 1987), the petioles from the high CO_2 chambers tended to have lower NO_3^- levels, which is possibly a dilution due to higher carbohydrate levels with high CO_2. No visual symptoms of N deficiency were observed.

The cotton rows were side dressed with Temik on 27 May in order to control early season insects everywhere in the field. Later, insecticides were applied as sprays to the plants outside the chambers, as indicated in Table 4.

2. Chamber construction

The CO_2-enrichment chambers were constructed following the design used in previous years (Kimball et al. 1983) but with enhancements for isolation of insect populations inside. Briefly, steel "T" fence posts were driven into the soil at the corners of the 3 by 3 m square chambers. An additional post was driven at the center of the north wall, and then 2 additional posts were driven, one 1 m north of the center post and the other 1 m north of the northwest corner post. The main door to the chamber was constructed between the center post in the north wall and the northwest corner post. The two north posts provided the frame for a vestibule, which served to minimize the passage of insects as personnel entered and left the chambers. The large air supply duct was installed on the south side. This orientation was opposite that of prior years because it was felt that the vestibules would have shaded the chambers more than the air duct if they were on the south. Plan view sketches of the chambers are shown in Fig. 1.

The top of the chambers (and of the vestibules) was covered with aluminum screen stapled to a wooden frame fabricated from 38 by 38 mm stock. Gaps between the frame and the chamber walls were sealed with transparent tape. Soil was diked up around the outside walls to seal the bottom. An outside door to the vestibules was constructed using screen and strips of Velcro fastener tape.

The aluminum screen used was 18 x 16 mesh and averaged 72.5% light transmittance to photosynthetically active radiation between 1200 and 1600 hours, as measured by a LiCor Model LI 185A quantum sensor.

3. Carbon dioxide concentrations

The CO_2 concentrations were again continually monitored and controlled with the automatic sampling/control system, as described previously

(Kimball et al., 1983). The overall CO_2 concentration means and standard deviations of the individual observations are tabulated in Table 5. In 1988, they averaged 372 $\pm$ 40 and 651 $\pm$ 48 μmol CO_2 mol^{-1} during daytime, 413 $\pm$ 49 and 662 $\pm$ 52 μmol mol^{-1} during nighttime, and 391 $\pm$ 49 and 656 $\pm$ 50 averaged μmol mol^{-1} over a whole (24 hr) day for the ambient and "650" treatments, respectively. Comparing with values for open-top chambers from 1987 (Kimball et al., 1987), the standard deviations in the enriched screen-top chambers from 1988 were about 2/3 as large as in 1987, which shows that the screen tops reduced the fluctuations in CO_2 concentration inside.

4. Temperature data

Aspirated psychrometers with ceramic wicks and copper-constantan thermocouples (Schnell, S. M., 1983) were used to measure the dry- and wet-bulb air temperatures in every chamber, and a duplicate pair was mounted on a weather mast in the open field west of the chambers to monitor ambient conditions. The psychrometers in the chambers were mounted to the southwest corner post with the intake pointed north at a slight upward angle, so that any drips from the wick would drain back away from the dry bulb. It was difficult to adjust the height, so they were fixed at a height of 130 cm, and then for uniformity, all of the outside psychrometers were also mounted at that height.

Maintenance of the psychrometers was a major job. The water reservoirs were refilled 3 times a week, at the same time checking to be sure the little aspiration blowers were operating properly and that the wick and dry bulb were positioned in the middle of the air stream with no obstructions. The wicks were replaced weekly with an alternate set of wicks from the week before that had been cleaned by boiling for 15 min. in 1 N nitric acid. If any wet bulb seemed consistently warmer by about 1°C than the wet bulbs in corresponding chambers, that wick was replaced and discarded. Finally, the temperature data were "cleaned" for this report by rigorous editing, as described later in the "Modeling of Plant Growth" section.

The daily maximum and minimum dry bulb temperatures are presented in Table 6. The temperature differences among chambers were small, with the means being identical for the ambient and 650 μmol mol^{-1} treatments. The screen tops shaded the chambers and decreased wind turbulence, as discussed previously, resulting in an average decrease of 1.7° in the maximum temperatures, compared to those from the weather mast.

5. Insect infestation and counting methods.

Cotton was naturally infested with beet armyworms before the chamber tops were secured. Populations were sampled over a 10-week period: egg masses, groups of newly hatched larvae, and individual larvae were counted. Counts were made daily for the 1st 8 wk. and then 3/wk thereafter. Adults were sampled weekly by black-light traps, counted,

and released back in the chambers the following morning. Adults were observed and sample-counted by night surveillance. Data from these samples and abiotic measurements (eg. temperature) were analyzed and plotted to determine rate of increase for eggs, larvae, and adults.

6. Results

The number of larvae per chamber are plotted against day of year in Figs. 2 and 3. Larval populations were ca equal at ≤ 5 /chamber to day 221. Two larval peaks of BAW occurred in each CO_2 enriched chamber between days 230-245 when they numbered 5-6 fold higher than those in respective ambient chambers. Similarly, they were 3-4 fold higher in a 3rd peak at about day 250, although absolute numbers of both groups had risen ca 8 fold over the earlier peaks. Adult peaks were offset from larval peaks by 5-8 days and numbers were very low relative to larval numbers. Egg masses were observed but too inconsistently for use.

7. Discussion

The large differences, especially the peak around day 250, between populations of BAW on CO_2 enriched cotton versus ambient cotton were rather surprising (Figs. 2 and 3). In a similar experiment, conducted simultaneously, with the cabbage looper (data not presented here), there were no significant population differences. We carefully examined the beginning populations of BAW to be sure the starting levels were equal. Equalization had been achieved by 1) securing the chamber tops 18 days before the start day (210), 2) treating the plots with insecticides to within 1 wk of the start day, and 3) by physically removing larvae up to the start day. At that time, the population levels were between 1-5 BAW/chamber and remained there until day 221. Therefore it appears that the increases were real population differences that developed between the two groups and not attributable to different starting levels.

We were not able to quantitatively relate the adult BAW population sample numbers (values of 0-26/trap night) to the absolute adult population numbers. However, the latter appeared to be inordinately low relative to the high numbers of BAW larvae present indicating survivorship from larval to adult stage was low. The increased foliage from CO_2 enrichment available to larval beet armyworms was not limiting until ca 40 days after the experiment started. The population was drastically reduced by death from a naturally-occurring virus that presented itself just as foliage became limiting.

8. Conclusions

This study demonstrated that on CO_2 enriched cotton, larval populations of beet armyworms increased but adult populations decreased. The increased development time of individuals as demonstrated in an earlier study (Kimball et al. 1987; Akey and Kimball 1989) may account for the higher than expected larval populations on CO_2 enriched cotton plants.

The low adult population was probably a consequence of low survival to the adult stage as reported in the earlier study of individuals.

These studies provide mere glimpses of the possible effects of CO_2 enrichment on insect herbivores. Investigation will need to continue to understand why some species are affected, e.g. beet armyworms and some are not, eg. pink bollworm (Akey et al 1988).

LONG-TERM EFFECTS OF ELEVATED CO_2 ON TREES

Most research about the effects of CO_2 on plant growth has been conducted on annual species (Kimball, 1983a,b, 1986), and consequently, we really know very little about what the increasing atmospheric CO_2 concentration will portend for forestry and other tree crop enterprises, where species life-spans are measured in decades (Kimball, 1985). Hence, to appropriately manage these important natural and cultivated resources in the totally different environment which will comprise the high CO_2 world of the future, it is necessary to discover now, by direct experimental means, the long-term effects of atmospheric CO_2 enrichment on trees. Therefore the main objective of this experiment is to determine the long-term effects of elevated CO_2 on the growth, photosynthesis, stomatal conductance, and foliage temperatures of trees, particularly orange trees.

Another aspect of the study will be to determine the effects of CO_2 enrichment on fruit production. Will there be more fruit? Will it be better fruit? Will the fruit be better able to withstand hard freezes? These and other pertinent questions will be addressed.

In the early years while the orange trees are small, all available space in the chambers is being used to investigate intermediate time-scale effects of CO_2 enrichment on other plant species. Therefore, we are also able to report the results of additional work conducted with agave and sorghum during 1988.

A. Open-Top Chamber Construction

Four open-top, clear-plastic-wall chambers were constructed in July of 1987 in a row along the south side of the Western Cotton Research Laboratory property. The materials and construction techniques were similar to those used previously (Kimball et al., 1983), except the chambers were larger (2.6 m wide by 5.3 m long by 2 m high). However, the height of the walls was increased to 3 m in December 1988 to accommodate the increasing height of the orange trees. The same type of blower was used (rated capacity of 1.2 m^3/S), so the air exchange rate was about 2.6 volumes per min for the 2-m-high chambers and about 1.7 volumes per min for the 3-m-high chambers. The large (46-cm-dia) plenum-type air duct was installed along the north wall, and four perforated 20-cm-dia lateral ducts extended at intervals from north to south across the chambers to distribute the air and CO_2.

B. CO_2 Treatments

From July to 17 November 1987, the chambers were all operated at ambient CO_2. As will be discussed later, this time without CO_2 enrichment allowed the orange trees to establish themselves, and all trees were of approximately the same size and condition when CO_2 enrichment commenced on 18 November 1987. The chambers on the ends (OT1 - east and OT4 - west) were enriched to 650 μmol CO_2 mol air^{-1} using the same automatic CO_2 sampling/control system as used in the other experiments (Kimball et al. 1983-1987). However, because of the larger size of chambers, the valves that regulated the CO_2 flow to the chambers often did not have sufficient capacity for the system to maintain the desired CO_2 concentration. Therefore, an additional CO_2 valve was installed parallel to the original valve for each of the enriched chambers. A constant low flow was maintained by the new valves, while the original valve continued to provide automatic control. Now the system could deliver enough CO_2 to meet the demand most of the time, but under calm conditions at night the steady flow from the secondary valves sometimes provided too much CO_2.

The CO_2 control strategy was also changed. Realizing that this is a long-term experiment, and that the ambient CO_2 concentration in the control chambers (OT2 and OT3) may approach 650 μmol mol^{-1} during the course of the experiment, it was decided to use a differential control strategy. Accordingly, the control algorithm in the computer was changed on 20 July 1988, so that the CO_2 concentrations in OT1 and OT4 are regulated to be 300 μmol mol^{-1} greater than those in OT2 and OT3, respectively.

The mean CO_2 concentrations in each chamber for each month during 1988 are listed in Table 7. From 1 January through 19 July 1988, the daytime CO_2 concentrations averaged 389 and 650 μmol CO_2 mol^{-1} for the ambient and enriched chambers, respectively, with higher ambient values at night. From 22 July through 31 December 1988 the mean daytime CO_2 concentrations were 387 and 690 μmol mol^{-1}.

These values of ambient CO_2 concentration (Table 7, Table 5) are rather sharply higher than the 344 μmol mol^{-1} reported a year ago for the CO_2-WATER-NITROGEN experiment (Kimball et al., 1987, Table 6), and they are also higher than general values being reported for the globe. Accordingly, extra precautions were taken to verify the accuracy of the equipment. The CO_2 analyzer is automatically calibrated hourly using zero and a high span gas (near 1000 μmol mol^{-1}), so extra full calibrations were done using 5 primary standards with concentrations at about 200, 350, 500, 700, and 900 μmol mol^{-1} (as well as zero, N_2). Standard gas was taken out to the chambers and allowed to flow through the entire sampling system, and correct values were observed with the analyzer. Therefore, for some unknown reason the level of CO_2 around our laboratories appears to have risen about 45 μmol mol^{-1} within a short period of time. There have been numerous light industrial

buildings constructed adjacent to the field during the last year, but whether they could represent a source of CO_2 of this magnitude seems doubtful.

C. Orange Trees

In July of 1987, two sour orange (Citrus aurontium) were transplanted into each of the four open-top chambers. Sour orange was chosen because it is particularly disease and frost resistent and is commonly used for root stock of commercial citrus orchards in the area as well as for an ornamental.

The eight sour orange trees in the four chambers have all been treated identically from the inception of the experiment, being manually irrigated at periods deemed appropriate for normal growth requirements. They have received very little fertilization, being treated with a commercial NPK mix on 4 February 1988, as recommended for young trees.

The only data which have been routinely collected on the trees pertain to tree height and trunk area at the base of the tree and at heights of 15, 30, 45, and 60 cm above the ground. These measurements are summarized on Table 8. As can be seen there, the trees were very comparable for several months at the beginning of the experiment; but about half-way through 1988, the trees in the +300 ppm CO_2 treatment began to grow faster than the trees in the ambient treatment. At the start of 1989, for example, the mean cross sectional areas of the trunks of the CO_2-enriched trees were 48%, 66%, 56%, 82%, and 102% greater than those of the ambient-grown trees at the tree base and at heights of 15, 30, 45, and 60 cm above the ground, respectively.

D. Agave

Small agave buds were obtained from a single parent plant and planted directly into the soil of the "orange tree" chambers on 18 November 1987. Initial plant data plus results obtained from five subsequent harvests are contained in Table 9. On 2 September 1988 a second such experiment was begun, for which we have one harvest data set in addition to the initial plant characterization.

A quick scan of the data reveals little effects of CO_2 enrichment in the winter, but a rather large growth stimulation in summer, resulting in a 58% increase in dry weight and a 53% increase in leaf area by 24 August from CO_2 enrichment. Evidentally, this CAM plant has a positive CO_2 x environment interaction similar to that observed previously with C3 plants (Allen et al. 1988, 1989).

E. Sorghum

1. Introduction

Many controlled environment experiments have shown that increasing atmospheric CO_2 causes an increase in net photosynthesis (Pn) of C3 plants and, to a lesser degree, C4 plants also. In an extensive review of the subject, Cure (1985) concluded that Pn of C3 plants would increase by approximately 28% from a doubling of atmospheric CO_2, whereas Pn of C4 plants would increase by only 5%. Stomatal conductance of water vapor (Gs) decreased by 32 and 35%, respectively, for C3 and C4 crop species from a doubling of atmospheric CO_2.

Less is known, however, about how the atmospheric CO_2 concentration interacts with other climate variables, such as short-wave solar radiation intensity and air temperature, to affect Pn and Gs, particularly as these interactions occur in natural environmental settings. Growth responses of numerous crops have indicated that a positive interaction occurs with increasing temperature; that is, the relative effects of higher atmospheric CO_2 increase as temperature increases (Idso et al., 1987). Allen et al. (1988, 1989) have shown that CO_2 concentration interacts at least as strongly with solar radiation as it does with air temperature to affect Pn of two C3 plants. Therefore an experiment was conducted using the C4 species Sorghum bicolor, L. Moench with the object of identifying the interactive effects of CO_2 concentration and other environmental variables on Pn and Gs in the near-natural conditions of the open-top chambers.

2. Material and Methods

Hybrid grain sorghum (experimental line RS 610) was started from seed on 1 March 1988. Five seeds were planted in a peat and vermiculite mix (3:1) in each of 16 11.4-L pots and thinned to 2 seedlings per pot 2 weeks later. The plants were kept in a greenhouse for 30 days, then four pots were transferred to each of the four outdoor, open-top CO_2 enrichment chambers that were also used for the orange trees.

Each pot received 58 g of 14-14-14 slow-release fertilizer on 1 March and 1 April. Once in the open-top chambers, the pots were watered three times per week with distilled water.

Pn, Gs, and leaf minus air temperature (Tl-Ta) were measured hourly between 0700 and 1700 hr MST on 26 April, and 3 and 4 May 1988 using a LiCor 6200 portable photosynthesis measurement system. The measurements were made on the first or second leaf from the top of a single plant in each pot in each chamber. Short wave solar radiation was measured in an adjacent field with a Eppley pyranometer. Air temperature was measured inside of each chamber at a height of 1.5 m.

The experimental design consisted of two randomized blocks in which four subsample measurements were taken. Subsample averages were used in all statistical analyses.

3. Results

Air temperatures taken at the time of the physiological measurements ranged from about 17 to 36°C, with only a small difference in the temperature patterns among the three days. Short-wave solar radiation ranged from approximately 100 to 1150 W m^{-2}, with nearly identical diurnal patterns for all three days, which were virtually clear.

The diurnal Pn results are presented in Fig 4. Only small differences in Pn between the two CO_2 treatments occurred on 26 April and 3 May, although plants in the elevated CO_2 treatment had consistently higher Pn rates, 11.0%, averaged over all three days, than those in the ambient CO_2 treatment. On 4 May, the difference between the two CO_2 treatments was greater, 15.0%, when averaged over the entire day. Slightly higher air temperatures on 4 May may have contributed to the treatment differences by providing a more optimal environment for Pn, which, as previously shown for C3 plants (Allen et al., 1988 and 1989), promotes the expression of elevated CO_2 effects on Pn. However, this observed response was not large enough to result in a significant CO_2 by environment interaction, as will be demonstrated later.

The CO_2 treatment-induced differences in Pn (11.0%) averaged over all three days) are considerable less than those found for Azolla, 27.9% (Allen et al., 1988), and water lily, 32.4% (Allen et al., 1989), grown in ambient and 650 μmol CO_2 mol air^{-1}. This discrepancy can be attributed to sorghum's more efficient C4 carbon fixation mechanism which acts to concentrate CO_2 in the bundle sheath cells of the leaves, thus reducing photorespiration (Black, 1986). Increasing the external CO_2 concentration above ambient is, therefore, marginally less effective for the inherently more efficient C4 plants.

Over the entire range of environments experienced in this experiment, the relative difference in Pn between the two CO_2 treatments changed very little. This is apparent in Fig. 5, where the slope of the regression of the high CO_2 treatment onto the ambient CO_2 treatment is not different from 1.0 ($P < 0.05$), indicating the lack of a significant CO_2 concentration by environment interaction effect on sorghum Pn. The same regression for water lily is shown in Fig. 6 from Allen et al., (1989). For this C3 plant, the slope is significantly greater than 1.0 ($P < 0.05$), implying a significant CO_2 by environment interaction effect on Pn. A similar result was found with Azolla (Allen et al., 1988). For these C3 species, the relative difference in Pn between the two CO_2 treatments becomes greater, up to a maximum of about 70%, as the environment becomes generally more favorable for Pn.

Unlike Pn, Gs of sorghum varied greatly between the two CO_2 treatments on all three days. Averaged over all three days, the plants in the 650 μmol CO_2 mol air^{-1} treatment exhibited 27% lower Gs rates than those in the ambient CO_2 treatment (Fig. 7). Also in contrast to the Pn results, there was a significant CO_2 by environment interaction effect on Gs. As can be seen in Figs. 7 and 8, under conditions that resulted in generally lower Gs rates there was little difference in Gs between the two CO_2 treatments. However, as environmental conditions tended to promote higher Gs rates, the relative difference in Gs between the two treatments increased.

The diurnal leaf minus air temperature (Tl-Ta) patterns are shown in Fig. 9. The ambient CO_2 treatment produced consistently lower Tl-Ta values (cooler leaves) than the elevated CO_2 treatment. This result is consistent with the higher Gs values in the ambient treatment. During the early afternoon, the greater transpirational cooling of the leaves in the ambient treatment resulted in leaf temperatures approximately 1.0 to 1.5°C cooler than air temperature. Leaf temperatures in the high CO_2 treatment declined only to about air temperature, but not below, indicative of lower transpiration and Gs rates.

4. Conclusions

This experiment suggests that substantial savings of water can be expected by C4 plants if the atmospheric CO_2 concentration continues to rise as predicted. These water savings, when combined with the slight CO_2-induced increase in Pn, imply that a substantial increase in water use efficiency can also be expected.

The CO_2-induced leaf warming could possibly pose a problem in the future if air temperatures also rise due to the "greenhouse effect." In areas where high temperatures presently affect marginal production, the combination of a 1.5 to 4.5°C air temperature increase plus a CO_2-induced 1.0 to 1.5°C increase in leaf temperature could cause a negative impact on production potential. Fortunately, most C4 crops are relatively tolerant of high temperatures. Consequently, a CO_2-induced leaf warming may provide them an advantage in cooler climates that are presently suboptimal.

FIZZ/FACE EXPERIMENT

A. Materials and Methods

1. Culture of the experimental cotton crop

This was the third year of an experiment which involved the application of CO_2 to cotton in an open field, as done previously in 1986 and 1987 (Kimball et al., 1986, 1987). One method was to irrigate the cotton with carbonated (FIZZ) water, and the second was to release gaseous CO_2

from tubing at the base of the plants, a free-air CO_2 enrichment (FACE) experiment.

The cultural practices applied to the FIZZ/FACE plots were almost the same as those for the CO_2-INSECT plots described earlier. This included growing a winter green manure crop of barley, which was disked into the soil before it matured, and which should have masked some of the nitrogen differences introduced in 1987 (Kimball et al., 1987). Planting date, variety, tillage, etc. were all the same. A second herbicide application of Karmex (diuron) was applied as a sidedress only to the FIZZ/FACE plots on 26 May at a rate of 1.25 lb. per acre. Additional fertilizer was applied at the same time, as described later.

There were four replicates each of the control (C), FIZZ (Z), and FACE (A) plots. The plot plan was the same as in 1986 and 1987, except Reps 1 and 2 were moved about 20 m to the east. (The shift was possible because the southeast corner of the field was not used for open-top chambers, as it was in the previous two years.) The basic plot areas were 5 rows (40 inch, 1.016 m spacing) wide by 5 m long. The control and fizz plots were planted in 8 row strips, so there were 2 border rows on one side and 1 on the other. The tubing for the A plots was laid along a 20 m length of 20 rows, thus forming a 7 m border around the A plots. Weather data were again recorded on a mast installed in approximately the same physical location as in 1987, but because of the shift of Rep 1 and 2 to the east, the mast was close to the Rep 1 FACE plot in 1988. With reference to Fig. 1, it was located approximately 10 m north of the fence and about 10 m west of the S3 and N3 chambers.

2. FIZZ Irrigation and CO_2, Water, and Nitrogen Applications

The irrigation system was the same as used in the two prior years. Briefly, a drip irrigation system was used to apply the water. Because the capacity of the city water supply limited the area that could be irrigated at one time to about 800 m^2, the reps of the A plus C plots were irrigated as blocks, whereas all 4 reps of the smaller FIZZ plots were irrigated together.

The irrigation and rain amounts are presented in Table 10. The first 3 irrigations were applied by flooding with amounts estimated to be about 150 mm each time. The drip irrigation system was installed in early June and was first used on 10 June. The first application of carbonated water to the FIZZ plots was on 23 June. As before, the amount to apply each week was based on pan evaporation of the previous week (times leaf area index/3 up to a LAI of 3) with corrections for rainfall and over- or under-irrigations the previous week. The water was applied daily with the amounts to apply each day adjusted weekly. The FIZZ plots were irrigated generally starting about 08:00 each day, followed sequentially by the 4 reps of the FACE plus control plots.

As before, CO_2 was injected into the irrigation water for the FIZZ plots using a commercial carbonator (Carboflow, Inc.). When operating, the CO_2 flow rate was about 34 L/min (STP, 1.1 g/s), which was distributed to a total FIZZ plot area of 591 m^2 amounting to a CO_2 release rate of 1.9 mg m^{-2} s^{-1}. Multiplying by the total CO_2 application time of 230.4 hr (Table 10), the total amount of CO_2 used in the FIZZ plots was 1.55 kg m^{-2}.

Following the preplant application of ammonium sulfate-phosphate, an additional application of Urea (150 kg N/ha) was applied as a sidedress on 26 May (Table 11). Therefore, nitrogen fertilizer was applied approximately weekly to the FIZZ/FACE experiment plots by injection of Urea-ammonium nitrate solution (which contained both the NH_4^+ and NO_3^- form of N) into the drip irrigation system, as listed in Table 11. The total amounts of about 380 kg/ha were relatively high in order to further mask residual effects of differing amounts applied in 1987 (Kimball et al., 1987), in case the winter green manure crop of barley did not accomplish the task.

3. FACE system design, CO_2 use, and atmospheric CO_2 concentrations

The free-air CO_2 enrichment (FACE) experiment was performed using the same equipment and techniques as before (Kimball et al., 1986, 1987). The release rate was again 10 mg m^{-2} s^{-1}. However, the timing of the enrichment period was again changed. In 1986 the plants were enriched 11 hours per day from 06:00 to 17:00 beginning on 16 June and ending on 29 September (105 days and total CO_2 usage of 42 kg/m^2). In 1987 the daily enrichment period was shortened to 4 hours per day centered on solar noon (10:30-14:30 MST) with a seasonal enrichment duration of 94 days from 19 June until 21 September. The amount of CO_2 used in 1987 (13.5 kg/m^2) was about 1/3 that used in 1986, yet the growth response was about the same. In 1988 the daily enrichment period was kept at 4 hours but shifted to later in the afternoon, 12:00-16:00. The shift was done because greenhouse studies during the previous winter indicated that CO_2-enrichment while leaf starch content was highest in the afternoon would give the largest growth response. Enrichment started on 11 July and continued 51 days until 31 August. The total CO_2 usage was 7.34 kg/m^2.

Air sampling manifolds were mounted at 75% of plant height in each of the FACE plots and also in the Rep 1 control plot. The automatic sampling system was again used to continually sample the air sequentially (about 20 times per hour) and analyze the CO_2 concentrations. The 13:00-14:00, daytime, nighttime, and whole day mean CO_2 concentrations from 28 July through 27 August are presented in Table 12. Focussing on the 13:00-14:00 interval, the average CO_2 concentration in the enriched plots was about 489 μmol mol^{-1} or about 143 μmol mol^{-1} above ambient.

Independent measurements of the CO_2 concentrations were obtained with a Li-Cor 6200 Portable Photosynthesis System on 11 days during the season while taking leaf photosynthesis measurements. The means of these data are presented in Table 13, and they indicate that the afternoon CO_2 concentrations were about 362 μmol mol^{-1} while the FACE was operating. This is lower than the 489 μmol mol^{-1} discussed above that was measured with the automatic sampling system. This same phenomenon was observed last year (Kimball et al. 1987), and it is probably because the photosynthesis measurements were taken on leaves at the very top of the canopy where the concentration would be expected to be less than that at the 75% plant height. As in 1987, the CO_2 concentrations for the first leaf were again about 20 μmol mol^{-1} higher than those for the second. This difference in CO_2 concentration between the first and subsequent leaves is puzzling but possibly could be due to there being a greater amount of time for the chamber to thoroughly flush with "new" air before the first leaf's measurement.

B. Results

1. Leaf Area, Flower Production, Boll Retention, Biomass, and Yield

Daily flower counts, boll load, and rate of boll retention were obtained from tagging of white blooms five days each week throughout the season, as was done in prior years (Kimball et al., 1986, 1987). Blooms were tagged with day number on five meters of row in each replication. Boll loading for the weekend was calculated from interpolation of the data on the adjacent Friday and Monday.

Intermediate harvests consisting of three plants each week were performed. The plants chosen for harvest were from a row which did not border the final-harvest row. They were removed each week from within a particular meter of row, proceeding systematically down the row to the next meter and so on. Counts were made on the harvested plants of the numbers of squares, flowers, bolls, and abscised sites. The plants were separated into stems, leaves, and bolls, and the dry weights of each were determined. Leaf area was also measured.

Final harvest data was obtained from all the plants in the five meters which were tagged for boll load. Plots were harvested on 12 September 1988, which was rather early. Therefore, green bolls at the time of harvest were given a final estimated weight for inclusion in the yield totals for each plot. The final weight of each green boll was assumed to be 80% of the average weight of an open boll from the same plot.

The final growth and yield results of the 1988 FIZZ/FACE experiment plots are presented in Table 14. Unlike the prior two years of this experiment, neither the FIZZ nor the FACE treatments had any significant effect on the biomass (top dry weight) production of the cotton plants. Even more discouraging were decreases in harvest index associated with the two treatments, resulting in yield reductions of 5 and 14% for the

FIZZ and FACE treatments, respectively. Lacking any known reason for such a poor growth response to the FIZZ treatment this year, we attribute it to natural variability. In the case of the FACE treatment, the time of application was shifted to afternoon based on some greenhouse experiment results which suggested that maximizing the amount of starch in the leaves going into the night, when most growth occurs, might promote overall growth and yield. Therefore, this application timing shift might have been responsible, but these results suggest that in the field perhaps the plant can make better use of extra-CO_2-promoted photosynthate earlier in the day when plant water and heat stresses are lower.

The average daily flowering, boll set, and boll retention percentages are given by week through the season in Table 15. The flowering patterns were very similar for all three treatments. However, from day 185 through about day 205 the boll-set numbers were higher for the control treatment, and it is likely that during this period of time, the die was cast for the lower harvest indices and yields for the FIZZ and FACE treatments compared to the control (Table 14).

An aggregation of the biomass (top dry weight) and seed cotton yield results for the three years (1986, 1987, 1988) of the FIZZ/FACE experiment are presented in Table 16. A statistical analysis of variance showed that year had a highly significant effect on biomass production. The FIZZ and FACE treatment increased biomass production by an average 8 and 12%, respectively, but these differences were significant only at a 0.1 probability level. In view of the negative yield responses in 1988 (Table 14), it was not surprising to find that no overall yield differences (Table 16) were statistically significant. However, it should be remembered that the amount and the timing of the CO_2 enrichment were altered each year for the FACE treatment, so this is not a completely valid analysis.

A rough picture of the practicality of the FIZZ and FACE treatments is presented in Table 17. In none of the years was the value of the yield increase sufficiently large to pay for the cost of the CO_2 for the FIZZ treatment. The yield increases observed here were considerably smaller than the +70 and +53% reported by Mauney and Hendrix (1988) in the greenhouse experiment that provided the impetus for doing such a field experiment. Mauney and Hendrix also showed by isotope analysis that the carbon from the CO_2 in the irrigation water did not enter the plants in any significant amounts. Therefore, the FIZZ irrigation treatment must really be regarded as a soil treatment (i.e. irrigating with carbonic acid), and indeed Mauney and Hendrix found some significant differences in uptake of P, Zn, and Mn from their potting mix. It is conceivable that under some field soil conditions (i.e. more alkaline than our field) yield responses more like those of Mauney and Hendrix might be obtained. Also, CO_2 prices vary widely by geography and by volume of use, so prices lower than the $160/Mg used in Table 17 may be available. Thus, the FIZZ treatment might be an effective yield-enhancing

treatment under some field conditions, and its feasibility deserves further study.

The costs for the CO_2 in the FACE treatment, on the other hand, far exceeded the value of the cotton (Table 17). Going from 1986 to 1988, we shortened the duration of the CO_2 treatment and also changed the enrichment time during the season (full canopy in 1987 and 1988) and during the day (around solar noon 1987, afternoon 1988) in an effort to reduce cost while maintaining the effectiveness of the application. Thus, CO_2 enrichment of the atmosphere of an open field costs far too much to be practical, and therefore, CO_2 enrichment is really only economical in greenhouses (e.g. Enoch and Kimball 1986). However, the method does have potential as an experimental technique to study the effects of the increasing atmospheric CO_2 concentration (as was our main objective for the 1986 experiment).

2. Photosynthesis and Stomatal Conductance

Net photosynthesis and stomatal conductance measurements were taken in the FIZZ/FACE experiment using a Li-Cor Portable Photosynthesis System. The procedure was similar to that already used in prior years (Kimball et al. 1986, 1987). Briefly, measurements were taken near midday on 3 leaves per plot choosing the youngest fully-expanded leaves for measurement. The measurements were taken weekly, usually Wednesday depending on sky conditions.

The net photosynthesis results are presented in Table 18. Like 1986 and 1987, there was no effect of the FIZZ treatment on net leaf photosynthesis. The mean rate was higher for the FACE treatment compared to the control, but the difference was not statistically significant, in contrast to the prior years when the FACE rate had been significantly higher than the control. The smaller difference in net photosynthetic rate for the FACE treatment this year is consistent with the smaller growth response also observed this year (Table 14).

The stomatal conductance results are also presented in Table 18. There were no statistically significant differences among treatments, which is consistent with the prior years' data.

3. Leaf Starch Content

Discs (six, 0.4 cm^2) were removed (avoiding major veins) for starch analysis from leaves in two transects across the FACE plots at about 2 pm on 28 July 1988. The wind during the day of sampling and the day prior to sampling was nearly continually from the west at a relatively low velocity (ca. 1-3 $m \cdot s^{-1}$), as recorded by the National Weather Service at Sky Harbor Airport about 4 km northwest of the field. Both transects were taken over a CO_2 enriched/non-enriched border. The "south" transect was across the upwind border from the control plot eastward to the FACE plot in Rep II (Kimball et al., 1987, Fig. 39). The "north" transect

was across the downwind border from the FACE plot eastward to the control plot in Rep. III. The transects were about ten feet wide and oriented across the rows. Ten plants in every other row had punches removed for analysis.

The leaf discs were analyzed for starch by a novel technique which avoided disc homogenization. They were collected into ice-cold 80% ethanol and stored at -80°C until assay (Hendrix and Peelen, 1987). The tubes containing the discs were heated to 80°C for 15 min and the ethanol decanted. Fresh ethanol was added and the hot extraction repeated. This was continued until the discs were no longer green (ca. four extractions). After pouring off the last ethanol rinse, dilute NaOH was added to the discs and the tubes were placed in a boiling water bath. After this treatment, the tubes were cooled and the NaOH neutralized with acetic acid. Starch in the discs was then digested with amyloglucosidase (Brown and Huber, 1988). Glucose solubilized by this treatment was detected by an enzymatic assay employing glucose oxidase coupled to the chromophore 3,3',5,5'-tetramethylbenzidine (D. L. Hendrix, in preparation).

Leaf starch along the "south" (upwind) transect (Fig. 10) showed a pronounced increase near the CO_2 enrichment boundary. This sharp increase was not found in the "north" (downwind) transect data. This difference was likely due to the fact that the wind blew steadily from the west during this experiment, which would have obscured the north transect (i.e., the downwind) boundary but not the south transect (i.e., the upwind) boundary. Other evidence in support of this conclusion is the fact that the starch in the entire north transect samples are much higher than that in control plots some distance from the CO_2 release areas, which averaged about 7-12 mg glucose$\cdot$dm^{-1} (data not shown). It appears that this technique can be utilized to measure the physiological response of cotton plants to free air CO_2 release and even to delineate the effective area of CO_2 release in FACE experiments.

MODELING OF PLANT GROWTH

Most of the 1988 plant growth modeling effort consisted of continuing to prepare the Phoenix open-top chamber and open-field validation data sets (Kimball et al., 1983-1987) for publication, and the first draft of a major report has been prepared. As discussed last year, this involved much editing to be sure no bad data were included. In the case of psychrometers, which were used to measure the air dry and wet bulb temperatures in every plot and outside, the data from replicate plots were graphed together against time through the season. Generally, the agreement was very close, but there were always some times during the season when there were discrepancies, which could often be explained by corrective actions recorded in the logbook. Because most psychrometer errors (water reservoir dry, dirty wick, wick touching wall, blower worn out) are in the direction to cause the wet bulb to be too warm, the one with the coldest wet bulb was usually taken to be correct. For those

times when one of the psychrometers was known to be in error, the temperatures of its mate were taken instead.

Occasionally there were gaps in the data caused by instrument malfunctions, and, also at the beginning of each season there was a lag between planting the field and installing all the equipment. As discussed above, missing or bad psychrometer data could usually be replaced by that from the other replicate plot. When data from a replicate plot was unavailable, however, other data were utilized. First, if another experiment was underway simultaneously at the USWCL, the weather data from that experiment were obtained. If no such local data were available, "outside" data were obtained from the Climatological Laboratory at Arizona State University, about 6 km to the east, and also from the National Weather Service at Sky Harbor Airport, about 4 km to the northwest. Whenever these other data were to be utilized, a graph was made of data from the outside source and that of a particular missing (or malfunctioning) instrument for 2 or 3 weeks when that instrument was working, and a regression equation was obtained. Then the gaps were filled using the outside data but adjusted to the particular plot using the regression equation.

In addition to "cleaning" the actual data, the format for presentation of the data came under considerable review and revision. Originally, the plan was to follow the format used by the cotton growth model GOSSYM (Baker et al, 1983). During 1988, we became aware of an effort to standardize the file structure and format of the input and validation data for crop growth models. Operating under the auspices of the International Benchmarks Sites of Agrotechnology Transfer (IBSNAT) Project, a group of plant growth modelers wrote IBSNAT Technical Report 5, Decision Support System for Agrotechnology Transfer (DSSAT), Documentation for IBSNAT Crop Model Input and Output Files, Version 1.0. Although cotton was not one of the crops considered by IBSNAT, nevertheless, this document made substantial progress toward specifying what pertinent variables needed for input and for validation of crop growth models (minimum data set) and how these variables are to be organized into a standard file structure and format.

Desiring that our data be useable for validating as many future cotton growth models as possible, we reorganized the file structure and format to conform as closely as possible to the IBSNAT standard. Furthermore, following the pattern used by IBSNAT for other crops, we proposed a standard for cotton, as presented in Tables 19, 20, and 21.

Because the amount of time required for preparing our data for publication was large, little actual progress was possible on development of a new cotton model, which would be capable of predicting the effects of increasing atmospheric CO_2 concentration and climate change on cotton growth, productivity, and water use. Fortunately, funding was obtained for a postdoctoral research associate position and an individual was

hired who began work at the beginning of 1989. Therefore, considerably more progress is anticipated in 1989.

DATABASE FOR RESPONSE OF VEGETATION TO CO_2 AND CHANGING CLIMATE VARIABLES

During 1988, another research activity was initiated with the objective to develop a database of virtually all the available data about the effects of CO_2 on important plant processes. A large body of literature already exists about the effects of CO_2 on important plant processes. The bibliography of Strain and Cure (1986) lists 1032 entries. In order to draw quantitative conclusions from this literature about the effects of high CO_2 concentrations on future crop production and ecosystem responses, it is desirable to extract and combine the data from these many studies, thereby improving the statistical probability and the reliability of resultant conclusions.

Kimball (1983a,b, 1986) assembled 430 and 770 observations, respectively, in his two analyses of prior studies about CO_2 effects on yield and growth. His 1983b and 1986b reports included 140 prior studies with 56 species. Similarly, Cure (1985) analyzed the results of 90 prior studies. She confined her report to 10 crop species (wheat, barley, rice, corn, sorghum, soybean, alfalfa, cotton, potato, and sweet potato), but expanded the number of plant processes to include short-term and acclimated carbon exchange rate (CER), initial and long-term net assimilation rate (NAR), biomass accumulation, root-to-shoot ratio, harvest index, stomatal conductance, transpiration, and yield.

Since 1983 and 1985, data about the effects of CO_2 on plants have been appearing in the literature at an increasing rate, stimulated in part by DOE-funded research on the "Response of Vegetation to Carbon Dioxide," as well as the increasing awareness of many other plant scientists about the increasing atmospheric CO_2 concentration. These data need to be analyzed together with all the prior data to test their consistency or inconsistency and improve the reliability of conclusions. Such an analysis will also serve to reveal gaps in the literature where additional experiments should be conducted.

As a means to accomplish this objective, a computerized database with data on the effects of CO_2 on plants was started. The important plant processes or parameters include: short-term and acclimated net photosynthesis (or carbon exchange rate, CER), initial and long-term net assimilation rates (NAR), biomass accumulation, root-to-shoot ratio, harvest index, stomatal conductance, transpiration, and yield, as selected by Cure (1985), but with the addition of carbon to nitrogen ratio (C/N) as an additional plant parameter important to herbivore and decomposer responses. Table 22 illustrates the coding form. In addition to information on the several plant processes at several CO_2 concentrations, additional classification information will be included, as shown by the list of codes in Table 23. Among these class variables

are species; photosynthetic type; crop type; season of year; CO_2 exposure method; age at termination or mature yield; any air pollutants in the study; the light, temperature, relative humidity, irrigation, salinity, and air pollution regimes; codes to designate whether the data are part of a planned interaction experiment with these variables; codes to characterize the quality of the CO_2 concentration control; and finally, CO_2 concentrations.

We have implemented the database on an IBM AT compatible computer. A data entry routine has been written by our computer personnel using the popular dBASE III PLUS program (Ashton-Tate Corp.), which produces screens similar to Table 22, so the user only has to fill in the blanks. Repetitive information from one study to the next can be copied from one "page" to the next, thereby saving time. Provision has been made to allow special comments, as deemed necessary.

As illustrated in Table 22, about 1000 characters' or 1k byte's worth of storage are required for each "page". Most experiments can be coded on one page, but interaction experiments require a separate page for each level of the interacting variable. Judging by the number of studies considered by Kimball (1983b, 1986) and by Cure (1985), less than 300 pages or 300 kb of storage will be required for the amount of data available in 1983, so even allowing for an increasing proliferation of CO_2 data, the size of the database will be relatively small and can easily be implemented on a PC. Because of its manageable size and implementation on an IBM PC or AT compatible equipment, it will be possible to make it readily available to others to search or test for particular effects in the data of interest to them.

At the end of 1988, over 500 "records" had been entered, a "record" being all the information associated with a single experiment with CO_2 as the only variable, as shown by Table 22. Interactive experiments require multiple records, one for each level of the other variables besides CO_2. It is difficult to estimate the total volume of information that will ultimately be extracted and entered, but approximately half of the reprints in the file of Kimball have been processed. It is planned to send a letter to active CO_2 researchers requesting additional reprints and data. Therefore, perhaps 1/4 of the "available" data have been entered.

SUMMARY AND CONCLUSIONS

The CO_2 concentration of the atmosphere is increasing and is expected to double sometime during the next century. Climate modelers have predicted that the increased CO_2 may cause significant climate changes. In order to predict what effects the increasing CO_2 and climate change may have on the productivity and water use of crops, the USDA-ARS U. S. Water Conservation Laboratory and the Western Cotton Research Laboratory conducted several research activities during 1988, and this document reports the progress made on those activities.

One laboratory and one field experiment were conducted to determine the effects of high-CO_2-grown host cotton on the development and temperature interactions and on population dynamics of the beet armyworm (BAW), Spodoptera exigua (Hubner). In the laboratory experiment, cotton plants were started in pots in CO_2-enriched (650 μmol mol^{-1}) and ambient greenhouses. After growth of the first two true leaves, they were transferred to individual cages within CO_2-enriched and ambient incubators and infested with 2-3 newborn BAW larvae. Temperatures studied to date include: 24, 27, and 30°C. Growth, development time, and survival are being analyzed. C:N ratios are being determined.

In the field experiment, cotton was grown in open-top CO_2-enrichment chambers similar to those used in prior years, except the tops were no longer completely open. Instead they were covered with "screen-tops" to isolate the insect populations intended for study. Three chambers were maintained at 650 μmol CO_2 mol^{-1} and 3 were at ambient (370 μmol mol^{-1}). After assuring that populations of BAW in the chambers were nearly identical in the spring, population counts were made through the course of the growing season, and an assessment was made of damage to the cotton. Significant findings from this experiment included the following:

1. Larval populations of BAW on cotton in CO_2 enriched chambers were 5-6 fold higher than those in respective ambient chambers.
2. Adult populations of BAW in CO_2 enriched chambers were inordinately low.
3. Significant increases in plant damage occurred from larval populations of BAW despite the deleterious effects of CO_2 enriched cotton on individual BAW.

Because most CO_2-enrichment research has been conducted on annual species and no long-term experiments have been conducted on trees whose life cycles span decades, such a long-term study was initiated in 1988 on sour orange trees. Sour orange (Citrus aurantium) was selected because it is particularly disease and frost resistant, and it is commonly used for root stocks in commercial orchards in the area. Eight trees were planted in 4 open-top chambers, 2 per chamber. Two of the chambers were enriched to 300 μmol CO_2 mol^{-1} above the concentration in the ambient control chambers. Average year-long daytime CO_2 concentrations were 668 and 388 μmol mol^{-1}, respectively. While the orange trees were small, excess space in the chambers was utilized for additional experiments with agave (a succulent CAM plant) and sorghum (a C4 plant). Significant findings from these experiments included the following:

1. Orange tree growth was greatly stimulated by the first year of CO_2 enrichment, with most of the effect coming during the hot summer months. Mean cross-sectional areas of the trunks of the CO_2-enriched

trees were 48, 66, 56, 82, and 102% greater than those of the controls at heights of 0, 15, 30, 45, and 60 cm, respectively, above the soil surface.

2. Small agave plants were increased 58% in dry weight by CO_2-enrichment from 18 November 1987 through 24 August 1988, with most of the effect coming in hot summer months.

3. Net photosynthesis of sorghum increased an average 11% by CO_2 enrichment over a 3 day intensive study period. At the same time stomatal conductance was reduced by an average 27%, which suggests significant savings of water can be expected by C4 plants in the future high-CO_2 world, and combined with the slight increase in net photosynthesis also suggests a substantial increase in water use efficiency.

Another experiment, called the FIZZ/FACE experiment, was repeated for the third time in 1988 where the effects of cotton growing in an open field (no chambers) was observed. The CO_2 was applied using two methods -- (1) irrigating with carbonated water (FIZZ) and (2) releasing CO_2 at the soil surface, a free-air CO_2 enrichment (FACE) experiment. The field was irrigated daily with ample water from drip irrigation tubing, the water for the FIZZ treatment being supersaturated with CO_2 from a commercial carbonator first. The CO_2 to the FACE plots was distributed through a second set of drip irrigation tubing at a release rate of 10 mg m^{-2} s^{-1} from 12:00 to 16:00 daily for 51 days. The average CO_2 concentration from 13:00 to 14:00 each of the enrichment days at 75% of plant height was 489 μmol mol^{-1}. The enrichment period was changed from the 06:00 to 17:00 for 105 days used in 1986 and the 10:30 to 14:30 for 94 days used in 1987. Control plots received normal irrigation and no free-air CO_2. There were four replications. Significant findings from the FIZZ/FACE experiment included the following:

1. Total (aboveground) biomass production was not significantly affected by the FIZZ or FACE treatments. However, both treatments lowered harvest index, resulting in seed cotton yield reductions of 5 and 14% for the FIZZ and FACE, respectively. Shifting of the FACE application time to afternoon in 1988 might have caused the negative result in 1988, in contrast to the positive growth responses in prior years.

2. An aggregation of the data from the 3 years of study showed that the FIZZ and FACE treatments increased above-ground biomass by an average 8 and 12% respectively (differences which were significant at only 0.1). With negative results in 1988 and positive in prior years, average 3-year yield increases of 5% were not statistically significant.

3. Neither net photosynthesis nor stomatal conductance were affected by the FIZZ treatment in all three years of the experiment. Similarity the FACE treatment did not affect stomatal conductance, but

it did increase net leaf photosynthesis all three years, although the increase was not statistically significant in 1988.

4. The FACE treatment markedly affected leaf starch contents as illustrated by an abrupt increase on the upwind border of the release area. It appears that leaf starch content could be utilized to measure the physiological response of plants and to delineate the effective area of CO_2 release in FACE experiments.

Data sets of cotton growth from prior years in open-top CO_2-enrichment chambers and from open-field plots were carefully edited and prepared for publication in a separate report. The data should be very useful for validating crop growth models, and were put into the file structure and format of a recently proposed standard for the inputs to such crop growth models.

A comprehensive computerized database was started of the quantitative information available in the literature about the effects of CO_2 on several important plant processes or parameters. The processes or parameters include yield, biomass, leaf stomatal conductance, leaf transpiration, harvest index, short- and long-term carbon exchange rates, short- and long-term net assimilation rates, root/shoot ratios, and carbon/nitrogen ratios. Classification variables such as species and photosynthetic type and experimental condition variables such as temperature and light intensity are also included. The database has been implemented on an IBM AT compatible computer, which should make it transportable. By the end of 1988, perhaps 1/4 of the available data had been entered.

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PERSONNEL

B. A. Kimball, D. H. Akey*, J. R. Mauney*, S. B. Idso, S. G. Allen, D. L. Hendrix*, J. W. Radin*, G. Peresta, S. Harris, R. LaMorte, B. Hefner*, L. Parker*, S. Johnson, L. Laird*, D. Fink*, S. B. Halderson*, G. Domer, D. Brummet*, J. Martinez, M. Eidenbock*.

*Western Cotton Research Laboratory

Table 1. Irrigation and rain amounts for the 1988 CO2-INSECT experiment.

Date	Day of Year	Mode[1]	Amount Applied
			mm
28-Apr	119	F	150.0
17-May	138	F	150.0
31-May	152	F	150.0
10-Jun	162	I	12.2
19-Jun	171	R	0.3
21-Jun	173	I	3.5
23-Jun	175	I	6.1
24-Jun	176	I	6.1
25-Jun	177	I	6.1
26-Jun	178	I	6.1
27-Jun	179	I	6.1
28-Jun	180	I	6.1
29-Jun	181	I	6.1
30-Jun	182	I	9.2
01-Jul	183	I	9.2
02-Jul	184	I	9.2
03-Jul	185	I	9.2
04-Jul	186	I	9.2
05-Jul	187	I	9.2
06-Jul	188	I	9.2
07-Jul	189	I	7.5
08-Jul	190	I	7.5
09-Jul	191	I	7.5
10-Jul	192	I	7.5
11-Jul	193	I	7.5
12-Jul	194	I	7.5
13-Jul	195	I	7.5
14-Jul	196	I	12.8
15-Jul	197	I	12.8
16-Jul	198	I	12.8
17-Jul	199	I	12.8
18-Jul	200	I	12.8
19-Jul	201	I	12.8
20-Jul	202	I	12.8
20-Jul	202	R	3.0
21-Jul	203	I	10.7
21-Jul	203	R	1.0

Table 1. - Contd

Date	Day of Year	Mode[1]	Amount Applied
			mm
22-Jul	204	I	10.7
23-Jul	205	I	10.7
24-Jul	206	I	10.7
25-Jul	207	I	10.7
26-Jul	208	I	10.7
27-Jul	209	I	10.7
28-Jul	210	I	10.7
29-Jul	211	I	10.7
30-Jul	212	I	10.7
30-Jul	212	R	8.6
31-Jul	213	I	10.7
01-Aug	214	I	11.0
02-Aug	215	I	11.0
02-Aug	215	R	5.1
03-Aug	216	I	11.0
04-Aug	217	I	9.3
05-Aug	218	I	9.3
05-Aug	218	R	1.0
06-Aug	219	I	9.3
07-Aug	220	I	9.3
08-Aug	221	I	9.3
09-Aug	222	I	9.3
10-Aug	223	I	9.3
11-Aug	224	I	9.2
12-Aug	225	I	9.2
13-Aug	226	I	9.2
14-Aug	227	I	9.2
15-Aug	228	I	9.2
16-Aug	229	I	9.2
17-Aug	230	I	9.2
18-Aug	231	I	12.0
19-Aug	232	I	12.0
20-Aug	233	I	12.0
21-Aug	234	I	12.0
21-Aug	234	R	7.1
22-Aug	235	I	12.0
23-Aug	236	I	12.0
24-Aug	237	I	12.0
25-Aug	238	I	7.0
26-Aug	239	I	7.0
27-Aug	240	I	7.0
28-Aug	241	I	7.0
29-Aug	242	R	7.9
29-Aug	242	I	7.0
30-Aug	243	R	2.8

Table 1. - Contd

Date	Day of Year	Mode[1]	Amount Applied
			mm
30-Aug	243	I	7.0
31-Aug	244	I	7.0
01-Sep	245	I	8.3
02-Sep	246	I	8.3
03-Sep	247	I	8.3
04-Sep	248	I	8.3
05-Sep	249	I	8.3
06-Sep	250	I	8.3
07-Sep	251	I	8.3
08-Sep	252	I	8.3
09-Sep	253	I	8.3
13-Sep	257	I	13.1
14-Sep	258	I	8.8
15-Sep	259	I	8.8
16-Sep	260	I	8.8
17-Sep	261	I	8.8
18-Sep	262	I	8.8
19-Sep	263	I	8.8
20-Sep	264	I	8.8
		TOTAL	1297.3

[1] F = flood irrigated
I = drip irrigated
R = rain

Table 2. Nitrogen fertilizer[1] applications to the plots of the 1988 CO_2-INSECT experiment.

Date	Day of Year	Nitrogen Form NH_4^+	NO_3^-
		----kg N/ha----	
21-Apr[2]	112	26.92	-
10-Jun	162	15.56	4.97
14-Jun	166		
15-Jun	167		
27 Jun	179	15.10	4.82
29-Jun	181		
30-Jun	182	15.10	4.82
05-Jul	187	15.10	4.82
08-Jul	190	15.10	4.82
13-Jul	195	15.10	4.82
20-Jul	202	15.10	4.82
27-Jul	209	15.10	4.82
29-Jul	211	15.10	4.82
09 Aug	222	15.10	4.82
16 Aug	229	15.10	4.82
	TOTALS	193.46	53.22
	TOTAL N	246.68	

[1] Except for 21 April, the fertilizer used was Urea-ammonium nitrate solution (32-0-0) (from Pure Grow Co., West Sacramento, CA), containing 7.75% ammoniacal nitrogen, 7.75% nitrate nitrogen and 16.5% urea nitrogen injected into the drip irrigation system.

[2] Ammonium sulfate-phosphate (16-20-0) broadcast before planting.

Table 3. Mean petiole NO_3^- nitrogen concentrations from cotton in the screen-top chambers of the 1988 CO_2-INSECT experiment.

	Treatment							
	Ambient CO_2				650 μmol CO_2 mol^{-1}			
Sampling Date	S1	N2	S3	Avg.	N1	S2	N3	Avg.
	- - - - g kg^{-1} - - - -				- - - - g kg^{-1} - - - -			
16 June	2.62	3.19	2.90	2.90	1.72	2.12	1.32	1.72
5 July	1.53	2.14	1.50	1.72	1.17	1.20	1.15	1.17
15 July	1.47	1.05	1.57	1.36	0.54	1.31	1.01	0.95
Avg.				1.99				1.28

Table 4. Insecticide applications applied to the 1988 cotton crop.

Date	Material	Quantity	Field Applied
27 May	Temik	3 lb/acre	Side dress 1 acre (Wilson excluded)
8 Jun	Malathion-50	6 tb/3 gals total	Six chambers
30 Jun	Dimilin	204 g + 1/3 qt. Commate/acre	All fields except Wilson & six chambers
6 Jul	Dimilin & Kelthane	3 g Dim + 2 tb Kelt/ 3 gals total	Six chambers
9 Jul	Malathion-50	6 tb/3 gals total	" "
12 Jul	Malathion-50	6 tb/3 gals total	" "
14 Jul	Thuricide, HP	2-1/2 qt/field	Three acres except the six chambers
16 Jul	Malathion RTU	32 oz/acre	" "
19 Jul	Dimilin	204 g + 1/3 qt Commate/acre	" "
21 Jul	Malathion-50	6 tb/3 gals total	Mauney plots only + chamber S_3
22 Jul	Orthene; Lorsban	1.83 lbs + 2 pints Lorsban/acre	Three acres except the six chambers
31 Jul	Orthene; Lorsban	1 lb/acre	" "
12 Aug	Karate	3.15 oz/acre	" "
26 Aug	Karate	3.15 oz/acre	" "
31 Aug	Malathion ULV-truck	32 oz/acre	" "
4 Sep	Malathion RTU	32 oz/acre	" "
10 Sep	Malathion RTU	32 oz/acre	" "
17 Sep	Malathion RTU	32 oz/acre	" "
1 Oct	Malathion RTU	32 oz/acre	Three acres except the six chambers
6 Oct	Malathion TU	32 oz/acre	" "
8 Oct	Malathion RTU	32 oz/acre	" "
15 Oct	Malathion RTU + ULV	36 oz/acre	" "

Table 5. Daytime, nightime, and whole day mean screen-top chamber CO_2 concentrations and the corresponding standard deviations of the individual observations from 20 May through 19 September of the 1988 CO_2-INSECT experiment.

Rep.	Plot No.	Ambient	Plot No.	650
		CO_2 Treatment		
		μmol mol^{-1}		μmol mol^{-1}
Daytime:				
1	S1	370 ± 41	N1	650 ± 42
2	N2	373 ± 40	S2	653 ± 55
3	S3	372 ± 40	N3	650 ± 46
Average		372 ± 40		651 ± 48
Nighttime:				
1	S1	403 ± 40	N1	656 ± 44
2	N2	419 ± 50	S2	674 ± 67
3	S3	417 ± 56	N3	656 ± 45
Average		413 ± 49		662 ± 52
Whole (24 hr) day:				
1	S1	385 ± 43	N1	653 ± 43
2	N2	395 ± 51	S2	663 ± 62
3	S3	393 ± 53	N3	653 ± 46
Average		391 ± 49		656 ± 50

Table 6. Daily maximum (MAX) and minimum (MIN) temperatures for the 1988 CO_2-INSECT experiments.

DAY	AMBIENT CHAMBERS						650 μmol mol^{-1} CHAMBERS						WEATHERMAST			
OF	S1		N2		S3		N1		S2		N3		EAST		WEST	
YEAR	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
150	-	-	-	-	-	-	-	-	-	-	-	-	29.4	17.6	29.3	16.3
151	-	-	-	-	-	-	-	-	-	-	-	-	23.5	12.4	23.3	12.1
152	-	-	-	-	-	-	-	-	-	-	-	-	28.3	10.6	28.3	9.1
153	-	-	-	-	-	-	-	-	-	-	-	-	33.2	14.4	33.1	14.6
154	-	-	-	-	-	-	-	-	-	-	-	-	38.4	17.4	38.0	17.6
155	-	-	-	-	-	-	-	-	-	-	-	-	40.2	21.2	39.9	21.4
156	-	-	-	-	-	-	-	-	-	-	-	-	41.6	22.0	40.8	22.3
157	-	-	-	-	-	-	-	-	-	-	-	-	39.3	22.4	38.7	22.5
158	-	-	-	-	-	-	-	-	-	-	-	-	36.8	18.3	36.2	18.5
159	-	-	-	-	-	-	-	-	-	-	-	-	35.1	14.8	34.8	15.0
160	-	-	-	-	-	-	-	-	-	-	-	-	36.2	16.5	35.8	16.8
161	-	-	-	-	-	-	-	-	-	-	-	-	37.9	16.0	37.5	16.8
162	-	-	-	-	-	-	-	-	-	-	-	-	35.8	18.3	37.3	22.0
163	-	-	-	-	-	-	-	-	-	-	-	-	34.5	14.6	37.1	17.9
164	-	-	-	-	-	-	-	-	-	-	-	-	-	18.7	-	20.0
165	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
166	-	-	-	-	-	-	-	-	-	-	-	-	38.6	19.5	38.6	19.7
167	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
168	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
169	41.3	27.7	40.5	27.3	41.5	27.4	40.8	27.5	41.1	27.6	40.7	27.2	40.1	27.4	40.3	27.6
170	36.8	26.2	36.1	26.2	36.4	25.8	36.5	26.1	36.4	25.8	36.1	25.9	37.0	26.2	37.2	26.2
171	40.6	24.5	39.6	24.4	40.2	24.3	40.3	24.7	40.2	24.4	39.5	24.2	39.4	23.8	39.5	25.0
172	40.6	27.4	40.2	27.4	41.1	27.3	41.0	27.4	40.9	27.5	40.3	27.3	39.3	27.0	39.2	26.9
173	42.9	26.7	41.9	26.6	42.8	26.5	42.8	26.3	42.5	26.7	42.1	26.4	42.4	26.9	42.3	27.0
174	44.6	26.6	43.5	26.6	44.2	26.2	44.6	26.4	44.1	26.4	43.6	26.3	43.9	25.9	43.9	25.9
175	42.6	29.4	41.8	29.4	43.2	29.1	42.6	29.3	42.5	29.2	42.6	29.1	42.6	28.6	42.8	28.6
176	39.9	28.1	38.1	28.1	39.7	28.2	39.8	28.6	39.7	28.4	39.4	27.6	38.9	27.7	39.0	27.6
177	40.0	26.6	38.6	26.5	39.9	26.2	39.8	26.9	39.3	26.1	39.2	26.2	40.2	25.6	40.4	25.7
178	38.9	23.8	37.3	23.8	38.7	23.2	38.7	24.4	38.0	23.3	38.2	23.3	38.3	23.5	38.5	23.6
179	39.4	-	37.8	-	39.5	-	39.3	-	38.4	-	38.9	-	39.3	-	39.2	-
180	35.3	27.2	34.1	27.3	35.5	27.3	35.4	27.5	35.3	27.0	35.2	27.3	35.5	28.0	35.6	28.2
181	37.2	26.3	35.6	26.2	37.2	25.9	37.0	26.6	36.9	25.7	36.7	26.0	37.0	26.3	37.0	26.4
182	37.6	26.8	36.1	26.5	37.9	26.7	37.7	26.9	37.4	26.4	37.5	26.6	38.5	27.1	38.6	27.2
183	36.8	26.0	35.3	25.8	36.5	25.1	37.0	26.3	36.8	25.4	36.9	25.5	38.1	26.0	38.4	26.0
184	-	27.5	-	27.1	-	26.9	-	27.7	-	26.8	-	27.0	-	27.5	-	27.6
185	36.7	-	35.0	-	36.8	-	36.7	-	36.4	-	36.5	-	38.0	-	38.4	-
186	35.9	24.9	34.5	24.5	36.0	24.3	36.4	25.3	35.3	24.1	35.6	24.4	37.5	25.0	37.7	25.2
187	38.0	28.0	36.0	27.8	37.3	27.5	38.4	28.6	37.0	27.4	37.1	27.8	38.7	28.1	38.8	28.1
188	36.5	26.7	34.6	25.8	36.4	25.7	37.0	26.6	35.8	25.6	36.2	25.5	38.0	28.2	38.3	28.4
189	35.9	29.0	34.2	28.5	36.2	28.9	36.5	29.0	35.4	28.6	35.7	28.8	37.6	29.7	37.9	29.6
190	36.5	28.2	35.8	27.5	36.7	27.6	37.0	28.5	36.1	27.4	36.3	27.2	38.3	28.0	38.6	28.0
191	37.1	29.6	36.6	28.8	37.1	29.0	38.2	29.7	36.8	29.0	37.3	28.9	38.1	29.1	38.5	29.1
192	35.4	25.9	33.6	25.3	35.5	25.3	35.9	26.3	34.7	25.2	35.3	25.2	36.6	25.2	36.9	25.2
193	33.7	24.6	32.4	23.9	33.5	24.0	34.4	24.7	32.9	23.9	33.5	23.9	34.3	24.2	34.6	24.2
194	34.9	23.7	33.2	23.0	34.4	22.6	35.6	24.4	33.8	22.5	34.5	22.8	36.0	23.9	36.2	24.3
195	35.9	21.1	33.2	20.2	34.5	19.6	36.9	21.9	34.4	19.5	34.4	19.5	36.5	21.9	37.0	22.3
196	36.6	23.0	33.9	22.1	35.4	21.6	37.4	23.5	34.8	21.8	35.5	21.5	38.1	23.5	38.5	24.0
197	35.4	22.5	32.9	21.8	34.6	21.1	35.5	23.1	33.8	21.2	34.2	21.6	37.2	22.8	37.7	23.3
198	35.3	24.6	32.7	23.8	34.5	23.9	35.5	25.0	33.7	23.9	34.1	23.7	38.5	24.4	39.2	24.7
199	34.1	27.8	32.2	26.3	34.1	27.8	34.2	28.0	33.1	26.6	33.8	26.4	36.5	27.7	37.2	28.1
200	32.5	27.5	30.8	26.9	32.4	26.9	32.4	27.7	31.8	26.8	31.7	27.0	33.2	27.2	33.7	27.4
201	33.6	24.7	32.2	24.4	33.5	24.3	33.4	25.2	32.8	24.2	32.9	24.4	34.2	24.3	34.7	24.3
202	34.6	23.4	33.1	23.2	34.1	23.2	34.6	23.7	33.2	23.0	33.8	23.2	35.8	24.5	36.4	22.6
203	34.5	25.0	33.4	24.5	34.8	24.4	34.8	25.3	33.9	24.3	34.0	24.3	36.5	24.6	37.0	22.8
204	34.7	26.9	33.4	26.5	34.6	26.4	34.8	27.1	34.2	26.4	33.9	26.2	36.9	26.0	37.5	26.3
205	34.0	24.9	33.1	24.7	33.9	24.1	34.4	25.7	33.4	24.3	33.5	24.4	36.2	25.0	37.2	25.8
206	33.8	27.7	32.6	26.8	33.8	26.8	34.2	28.2	33.0	26.7	33.1	26.5	36.1	28.7	37.0	29.0
207	33.7	25.7	32.7	25.4	33.4	25.0	34.0	26.4	33.0	25.2	33.2	25.0	35.8	25.3	36.8	25.9
208	33.1	26.1	32.0	25.7	32.7	25.7	33.3	26.3	32.6	25.9	32.8	25.7	35.0	25.4	35.8	25.7
209	33.8	25.9	33.0	25.4	33.5	25.2	33.9	26.3	33.5	25.1	33.4	25.3	34.1	26.5	35.0	27.2
210	32.9	26.0	31.7	25.6	32.4	25.7	33.1	26.0	32.3	25.9	32.1	25.6	33.4	25.3	34.3	25.6
211	33.1	22.2	31.9	21.9	32.7	22.0	33.3	22.1	32.6	22.2	32.5	21.8	34.4	21.6	35.2	21.5
212	31.1	21.2	30.7	21.0	30.9	21.1	30.5	21.2	31.4	21.2	30.4	21.0	30.9	21.2	31.5	21.0
213	31.8	24.6	31.3	24.1	31.4	24.4	31.3	24.6	31.4	24.4	31.3	24.5	31.4	24.1	31.9	24.5
214	32.2	23.3	31.7	23.1	31.8	22.7	31.7	23.3	31.7	23.0	31.7	23.4	33.0	23.0	33.4	23.4
215	32.2	24.7	30.8	23.0	31.6	24.0	31.0	23.6	31.3	24.0	31.2	23.9	33.5	23.9	33.6	24.4
216	32.7	25.2	31.4	24.6	32.0	24.6	31.5	24.9	31.9	24.3	31.7	24.5	33.2	24.3	33.6	25.3
217	29.4	24.3	28.8	22.9	28.7	23.3	29.8	24.5	28.3	23.0	28.7	23.5	30.4	24.3	30.7	24.4
218	31.5	23.8	30.9	23.4	31.2	22.9	31.2	24.2	31.0	23.1	31.2	23.4	32.0	23.3	32.2	23.7

Table 6 (contd). Daily maximum (MAX) and minimum (MIN) temperatures for the 1988 CO_2-INSECT experiments

DAY OF YEAR	AMBIENT CHAMBERS						650 μmol mol^{-1} CHAMBERS						WEATHERMAST			
	S1		N2		S3		N1		S2		N3		EAST		WEST	
	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN
219	32.1	26.5	31.6	26.0	32.1	25.9	32.2	27.1	31.2	25.7	31.9	25.9	32.5	25.9	34.1	26.5
220	31.1	23.0	30.8	22.3	31.2	22.4	31.7	23.7	31.2	21.2	31.2	22.3	32.9	21.9	33.4	22.5
221	30.4	20.4	30.0	19.9	30.5	19.3	30.9	21.5	29.8	17.9	30.6	19.6	30.9	18.6	31.0	19.4
222	30.6	20.9	31.2	20.4	31.2	19.6	31.9	22.0	30.0	19.3	31.3	20.0	32.4	20.1	32.5	19.2
223	32.1	19.1	32.8	18.6	32.0	18.2	33.3	20.3	30.9	17.6	32.3	18.3	33.7	18.6	34.6	17.4
224	31.1	24.4	32.2	23.9	30.9	23.7	32.6	25.6	29.9	23.1	31.7	23.3	34.0	24.0	34.4	24.8
225	31.6	24.6	33.6	24.2	31.9	23.9	33.4	25.7	31.2	23.5	31.4	23.8	34.1	23.6	34.1	24.6
226	30.1	20.6	31.4	20.4	30.5	19.0	31.7	22.2	29.0	19.1	31.1	19.3	32.7	18.9	33.4	20.0
227	32.3	19.9	32.6	19.7	31.7	18.7	33.4	21.2	31.8	18.5	31.8	18.9	34.4	18.1	34.9	19.7
228	30.5	23.8	31.7	24.1	31.4	22.9	32.2	25.3	29.8	23.1	31.8	23.1	32.6	22.8	33.8	23.8
229	31.3	23.0	33.0	23.1	31.9	22.1	33.6	24.6	30.1	22.2	32.5	22.1	33.6	21.4	34.6	22.4
230	33.2	24.1	34.0	24.2	32.8	23.2	35.6	25.6	32.3	23.1	33.9	23.3	34.6	23.8	36.0	25.0
231	32.5	26.4	32.8	26.7	32.1	25.3	34.3	28.4	31.0	25.6	33.3	25.6	34.2	25.5	35.4	26.8
232	31.5	26.2	31.8	26.5	32.2	25.5	32.6	27.5	30.4	25.6	32.6	25.7	33.5	24.9	34.8	26.1
233	30.5	23.6	30.5	23.9	30.4	23.8	31.4	24.6	29.7	23.7	31.1	23.6	30.8	24.0	31.1	24.0
234	27.1	23.7	26.8	23.4	27.7	23.6	27.4	23.4	26.9	23.4	28.1	23.5	27.6	22.8	27.7	21.3
235	30.3	23.2	30.5	23.2	30.4	22.8	31.1	23.6	30.1	22.8	30.8	22.7	31.4	21.9	31.4	22.3
236	31.8	24.4	32.5	24.8	32.2	24.3	32.9	25.3	31.4	24.1	32.7	23.8	33.0	24.4	33.1	25.0
237	31.0	23.2	31.4	23.7	31.4	22.9	31.8	24.3	30.6	23.1	31.6	22.5	33.2	22.1	33.1	23.2
238	31.0	25.3	31.8	25.2	31.7	24.4	32.4	26.1	31.0	24.5	32.3	24.7	33.9	24.5	33.8	25.5
239	31.1	25.4	33.8	25.1	31.2	24.0	32.7	26.4	30.6	24.4	32.2	24.3	34.4	23.9	35.0	25.6
240	29.9	24.9	30.6	24.9	29.7	24.3	31.5	25.6	29.3	24.5	30.7	24.5	33.0	24.2	33.6	24.9
241	30.0	22.6	31.3	22.6	30.5	22.4	32.3	22.6	30.3	22.4	31.5	22.4	32.6	23.1	32.6	22.1
242	32.8	21.9	33.1	22.0	32.7	21.5	34.4	22.3	30.4	21.4	32.7	21.4	32.7	22.0	31.8	21.2
243	30.3	22.1	31.8	22.0	31.1	22.0	32.1	22.0	30.4	21.9	32.0	21.7	32.7	22.1	33.0	21.3
244	31.6	23.7	32.1	23.4	31.1	22.9	32.8	24.0	31.2	23.0	32.3	23.0	33.4	23.4	33.7	24.2
245	31.8	23.6	32.6	23.5	31.8	22.5	32.9	24.0	31.6	22.8	32.0	23.1	34.0	23.5	34.9	24.2
246	32.8	23.5	34.6	23.5	33.0	22.2	35.5	24.0	32.1	22.8	34.2	22.6	34.3	23.0	35.3	23.9
247	33.4	25.3	35.3	25.3	34.4	24.0	36.0	26.2	32.3	24.5	35.1	24.6	34.8	25.5	35.5	26.3
248	33.1	24.5	34.2	24.6	33.5	23.0	34.7	25.1	31.2	24.0	34.3	23.6	33.5	24.1	34.4	24.9
249	32.4	22.0	33.1	22.3	33.2	20.9	33.0	22.7	30.7	21.6	33.7	21.3	33.2	22.0	33.8	22.9
250	31.5	18.6	33.0	17.9	31.7	17.1	32.9	18.7	29.5	17.3	33.2	17.2	33.5	17.9	34.2	19.2
251	-	18.0	-	17.1	-	16.4	-	17.7	-	16.4	-	16.4	-	17.7	-	18.9
252	30.8	20.3	31.4	19.7	31.3	19.0	31.7	20.5	30.2	18.7	32.6	19.5	34.1	19.1	34.7	20.0
253	31.5	20.0	32.2	19.4	31.9	18.2	32.4	19.8	30.8	18.7	33.8	18.8	35.1	19.2	35.8	20.3
254	32.2	21.9	32.3	21.7	32.9	20.5	33.4	22.4	31.3	20.7	33.0	21.0	34.7	21.8	35.2	22.8
255	32.0	22.6	31.6	21.9	32.2	21.1	33.2	22.9	28.9	21.0	32.0	21.1	34.9	21.8	35.5	23.2
256	32.3	21.0	32.0	21.5	32.8	20.9	31.9	21.4	29.4	20.0	32.0	20.7	33.1	22.1	33.6	22.5
257	31.2	16.2	31.2	15.7	32.1	14.5	31.6	16.5	29.2	15.0	32.3	14.2	31.6	15.1	31.8	16.4
258	30.1	14.8	29.8	14.6	31.4	13.4	30.5	15.3	29.6	12.7	31.3	13.4	32.1	14.6	32.2	15.4
259	31.4	15.5	31.7	15.0	32.8	14.3	31.7	16.2	30.2	13.7	32.3	14.2	34.8	15.6	35.3	16.5
260	33.0	16.3	32.5	16.1	34.4	15.2	32.6	17.5	31.2	15.0	33.5	15.5	36.6	16.3	36.6	17.2
261	32.9	16.4	31.7	15.9	35.0	15.2	32.8	17.1	31.3	14.7	33.1	15.2	36.3	16.3	36.3	17.1
262	31.4	16.5	34.8	15.2	33.8	16.2	31.1	17.6	29.7	15.2	31.8	15.9	34.4	16.2	34.4	17.0
263	35.9	14.2	36.2	14.7	35.6	14.7	37.0	16.3	31.5	13.9	32.3	14.4	35.5	15.2	35.4	15.9
264	35.6	17.1	31.6	16.8	36.5	17.7	32.6	17.9	36.1	17.0	33.1	17.5	37.7	19.3	37.5	19.6
AVG. (Days 169 -264)	33.8	23.7	33.4	23.4	33.9	23.0	34.4	24.2	33.0	22.9	33.8	23.0	35.2	23.4	35.6	23.8
AVG. OVER TREATMENT			MAX	MIN					MAX	MIN						
			33.7	23.4					33.7	23.4			MAX 35.4		MIN 23.6	

Table 7. Mean CO_2 concentrations and associated standard deviations in the open-top chambers for the CO_2-ORANGE-TREE experiment observed during 1988.

Averaging Interval	Cham.	Ambient Day	Ambient Nite	Ambient 24 hr	Cham.	+300 Day	+300 Nite	+300 24 hr
		μmol mol^{-1}				μmol mol^{-1}		
Enriched chambers controlled at 650 μmol mol^{-1}								
1-31 Jan	OT2	402 ± 42	427 ± 46	414 ± 46	OT1	649 ± 63	651 ± 68	650 ± 65
	OT3	398 ± 40	422 ± 43	409 ± 43	OT4	639 ± 49	642 ± 53	640 ± 51
	Avg.	400 ± 41	425 ± 45	412 ± 45		644 ± 56	647 ± 61	645 ± 58
1-29 Feb	OT2	400 ± 40	434 ± 47	416 ± 47	OT1	650 ± 63	649 ± 72	650 ± 68
	OT3	394 ± 38	424 ± 44	408 ± 43	OT4	647 ± 48	645 ± 57	646 ± 52
	Avg.	397 ± 39	429 ± 46	412 ± 45		649 ± 56	647 ± 65	648 ± 60
1-31 Mar	OT2	393 ± 39	425 ± 48	408 ± 46	OT1	637 ± 82	638 ± 83	638 ± 83
	OT3	390 ± 37	416 ± 44	402 ± 43	OT4	656 ± 47	652 ± 48	654 ± 47
	Avg.	392 ± 38	421 ± 46	405 ± 45		647 ± 65	645 ± 66	646 ± 65
1-30 Apr	OT2	387 ± 38	422 ± 51	403 ± 48	OT1	662 ± 64	658 ± 73	660 ± 68
	OT3	383 ± 36	411 ± 45	396 ± 43	OT4	654 ± 51	650 ± 52	652 ± 52
	Avg.	385 ± 37	417 ± 48	400 ± 45		658 ± 58	654 ± 63	656 ± 60
4-31 May	OT2	384 ± 38	420 ± 48	402 ± 47	OT1	656 ± 63	662 ± 72	658 ± 67
	OT3	381 ± 37	410 ± 41	395 ± 42	OT4	646 ± 80	648 ± 62	647 ± 72
	Avg.	383 ± 38	415 ± 45	399 ± 45		651 ± 72	655 ± 67	653 ± 70
1-30 Jun	OT2	387 ± 38	415 ± 46	401 ± 45	OT1	653 ± 65	660 ± 65	656 ± 65
	OT3	383 ± 36	408 ± 42	396 ± 41	OT4	639 ± 66	649 ± 70	644 ± 68
	Avg.	385 ± 37	412 ± 44	393 ± 43		646 ± 66	655 ± 68	650 ± 67
1-19 Jul	OT2	380 ± 39	401 ± 43	390 ± 43	OT1	654 ± 73	668 ± 81	660 ± 77
	OT3	378 ± 40	395 ± 39	386 ± 40	OT4	651 ± 65	645 ± 64	649 ± 64
	Avg.	379 ± 40	398 ± 41	388 ± 42		653 ± 69	657 ± 73	655 ± 71
1 Jan - 19 Jul	OT2	390 ± 39	421 ± 47	405 ± 46	OT1	632 ± 62	655 ± 73	653 ± 70
	OT3	389 ± 38	412 ± 43	399 ± 42	OT4	647 ± 58	647 ± 58	647 ± 58
	Avg.	389 ± 38	416 ± 45	402 ± 44		650 ± 63	651 ± 66	650 ± 64

Table 7. Contd

Averaging Interval	Cham.	CO_2 Treatment: Ambient Day	Ambient Nite	Ambient 24 hr	Cham.	+300 Day	+300 Nite	+300 24 hr
		- - - - μmol mol^{-1}	- - - - -			- - - - μmol mol^{-1}	- - - - -	
Enriched chambers controlled at 300 μmol mol^{-1} above ambient chambers:								
22-31 Jul	OT2	380 ± 36	396 ± 39	387 ± 38	OT1	692 ± 74	730 ± 111	709 ± 95
	OT3	376 ± 34	388 ± 37	382 ± 35	OT4	673 ± 79	682 ± 92	677 ± 85
	Avg.	378 ± 35	392 ± 38	385 ± 37		683 ± 77	706 ± 102	693 ± 90
1-31 Aug	OT2	386 ± 40	413 ± 51	399 ± 47	OT1	706 ± 89	743 ± 111	724 ± 101
	OT3	379 ± 36	397 ± 41	388 ± 40	OT4	673 ± 83	694 ± 96	683 ± 90
	Avg.	383 ± 38	405 ± 46	394 ± 44		690 ± 86	719 ± 104	704 ± 96
1-30 Sep	OT2	392 ± 41	452 ± 54	420 ± 57	OT1	710 ± 82	751 ± 102	729 ± 94
	OT3	380 ± 36	424 ± 46	401 ± 46	OT4	668 ± 77	686 ± 88	676 ± 83
	Avg.	386 ± 39	438 ± 50	411 ± 52		689 ± 80	719 ± 95	703 ± 89
1-31 Oct	OT2	399 ± 41	450 ± 49	422 ± 52	OT1	708 ± 101	750 ± 124	728 ± 114
	OT3	386 ± 36	425 ± 42	404 ± 44		678 ± 81	706 ± 95	691 ± 89
	Avg.	392 ± 39	438 ± 46	413 ± 48		693 ± 91	728 ± 110	710 ± 102
1-30 Nov	OT2	399 ± 51	446 ± 59	422 ± 60	OT1	715 ± 94	749 ± 123	732 ± 110
	OT3	386 ± 40	422 ± 50	403 ± 48	OT4	683 ± 85	706 ± 100	694 ± 94
	Avg.	393 ± 46	434 ± 55	413 ± 54		699 ± 90	728 ± 112	769 ± 102
1-31 Dec	OT2	396 ± 42	432 ± 52	413 ± 50	OT1	703 ± 109	735 ± 123	718 ± 117
	OT3	386 ± 37	420 ± 59	402 ± 51	OT4	675 ± 109	701 ± 95	687 ± 104
	Avg.	391 ± 40	426 ± 56	408 ± 51		689 ± 109	718 ± 109	703 ± 111
22 Jul-31 Dec	OT2	392 ± 42	432 ± 51	411 ± 51	OT1	708 ± 92	743 ± 116	723 ± 105
	OT3	382 ± 37	413 ± 46	397 ± 44	OT4	675 ± 86	696 ± 94	685 ± 91
	Avg.	387 ± 39	422 ± 48	404 ± 47		690 ± 89 (+303)	719 ± 105 (+297)	704 ± 97 (+300)
1 Jan-31 Dec	OT2	391 ± 40	426 ± 49	408 ± 48	OT1	676 ± 79	694 ± 92	684 ± 86
	OT3	385 ± 38	412 ± 44	398 ± 43	OT4	660 ± 71	669 ± 74	664 ± 73
	Avg.	388 ± 38	419 ± 46	403 ± 45		668 ± 75	681 ± 83	675 ± 79

Table 8. Mean orange tree growth parameters.

Year	Day	CO_2	Height	Trunk Area at: Base	15 cm	30 cm	45 cm	60 cm
		(μmol mol^{-1})	(cm)	mm^2				
1987	4 Dec	amb.	88	224	54	35	20	18
		650	96	154	67	42	26	23
		(% difference)	(+9)	(-31)	(+24)	(+20)	(+30)	(+28)
1988	6 Jan	amb.	90	199	72	46	26	20
		650	96	183	72	39	26	26
	9 Feb	amb.	90	199	72	46	29	23
		650	96	154	76	50	32	29
	8 Mar	amb.	97	207	76	50	32	23
		650	103	168	81	46	35	23
	11 Apr	amb.	98	250	92	72	46	35
		650	104	199	103	81	58	39
	8 May	amb.	102	268	109	87	54	46
		650	120	232	127	97	72	50
	20 Jun	amb.	120	347	161	121	92	58
		650	144	368	199	154	115	97
	2 Sep	amb.	131	401	191	140	109	76
		+300	162	460	268	207	183	168
	5 Oct	amb.	138	424	215	154	121	97
		+300	166	535	306	232	207	199
	4 Nov	amb.	145	448	224	161	134	109
		+300	181	589	326	259	232	215
	5 Dec	amb.	147	460	259	183	154	127
		+300	186	645	368	296	268	232
1989	5 Jan	amb.	148	436	241	183	147	115
		+300	186	645	401	286	268	232
		(% difference)	(+26)	(+48)	(+66)	(+56)	(+82)	(+102)

Table 9. Mean agave growth parameters.

Year	Day	CO_2	Dry Weight Tops	Dry Weight Roots	Dry Weight Total	Leaf Number	Leaf Length	Leaf Width[1]	Leaf Area[2]
		(μmol mol^{-1})	- - g plant^{-1} - -			No. plant^{-1}	- - - cm - -		m^2 plant^{-1}
First experiment:									
1987	18 Nov	amb.	2.16	0.29	2.45	--	8.8	--	--
	18 Dec	amb.	5.22	0.92	6.14	13.9	12.1	2.80	0.024
		650	4.92	0.90	5.82	13.4	11.7	2.90	0.023
1988	1 Feb	amb.	5.58	0.65	6.23	14.1	13.0	3.01	0.028
		650	5.94	0.76	6.70	13.6	13.0	3.08	0.034
	5 Apr	amb.	8.41	0.84	9.25	14.8	15.6	3.35	0.039
		650	13.48	1.79	15.27	15.4	18.4	3.85	0.055
	9 Jun	amb.	20.30	2.50	22.80	16.6	22.8	3.87	0.073
		650	28.34	4.51	32.85	17.6	26.4	4.08	0.095
	24 Aug	amb.	29.48	1.91	31.39	14.6	29.4	4.38	0.094
		+300	46.21	3.24	49.45	16.4	36.1	4.88	0.144
		(% difference)	(+57)	(+70)	(+58)	(+12)	(+23)	(+11)	(+53)
Second experiment:									
	2 Sep	amb.	2.45	0.59	3.04	10.2	12.9	2.64	0.017
	17 Oct	amb.	3.27	0.70	3.97	9.6	13.6	2.72	0.018
		+300	3.76	0.86	4.62	9.9	13.6	2.80	0.019

[1] Measured at the widest part, which was generally just a few cm from the base.

[2] Calculated assuming that the leaves are isosceles triangles.

Table 10. Irrigation and rain amounts for the 1988 FIZZ/FACE experiment.

Date	Day of Year	Mode[1]	FACE + CONTROL Rep 1	Rep 2	Rep 3	Rep 4	FIZZ Irrig. Amount	CO_2 Time
			- - - - - - - - mm - - - - - - -				mm	hr
28-Apr	119	F	150.0	150.0	150.0	150.0	150.0	0
17-May	138	F	150.0	150.0	150.0	150.0	150.0	0
31-May	152	F	150.0	150.0	150.0	150.0	150.0	0
10-Jun	162	I	12.2					
14-Jun	166	I		29.5			13.8	0
15-Jun	167	I			5.3	8.4		
19-Jun	171	R	0.3	0.3	0.3	0.3	0.3	0
21-Jun	173	I	3.5	5.3	1.4	6.9	5.3	0
23-Jun	175	I	6.1	7.4	5.8	6.7	5.5	2.1
24-Jun	176	I	6.1	7.4	5.8	6.7	5.5	2.1
25-Jun	177	I	6.1	7.4	5.8	6.7	5.5	2.1
26-Jun	178	I	6.1	7.4	5.8	6.7	5.5	2.1
27-Jun	179	I	6.1	7.4	5.8	6.7	5.5	2.1
28-Jun	180	I	6.1	7.4	5.8	6.7	5.5	2.1
29-Jun	181	I	6.1	7.4	5.8	6.7	5.5	2.1
30 Jun	182	I	9.2	7.2	8.9	7.3	8.5	3.1
01-Jul	183	I	9.2	7.2	8.9	7.3	8.5	3.1
02-Jul	184	I	9.2	7.2	8.9	7.3	8.5	3.1
03-Jul	185	I	9.2	7.2	8.9	7.3	8.5	3.1
04-Jul	186	I	9.2	7.2	8.9	7.3	8.5	3.1
05-Jul	187	I	9.2	7.2	8.9	7.3	8.5	3.1
06-Jul	188	I	9.2	7.2	8.9	7.3	8.5	3.1
07-Jul	189	I	7.5	8.9	7.5	9.5	9.3	3.3
08-Jul	190	I	7.5	8.9	7.5	9.5	9.3	3.3
09-Jul	191	I	7.5	8.9	7.5	9.5	9.3	3.3
10-Jul	192	I	7.5	8.9	7.5	9.5	9.3	3.3
11-Jul	193	I	7.5	8.9	7.5	9.5	9.3	3.3
12-Jul	194	I	7.5	8.9	7.5	9.5	9.3	3.3
13-Jul	195	I	7.5	8.9	7.5	9.5	9.3	3.3
14-Jul	196	I	12.8	12.1	13.6	13.3	12.2	4.3
15-Jul	197	I	12.8	12.1	13.6	13.3	12.2	4.3
16-Jul	198	I	12.8	12.1	13.6	13.3	12.2	4.3
17-Jul	199	I	12.8	12.1	13.6	13.3	12.2	4.3
18-Jul	200	I	12.8	12.1	13.6	13.3	12.2	4.3
19-Jul	201	I	12.8	12.1	13.6	13.3	12.2	4.3
20-Jul	202	R	3.0	3.0	3.0	3.0	3.0	0
21-Jul	203	I	10.7	11.4	11.2	11.3	11.1	3.9
21-Jul	203	R	1.0	1.0	1.0	1.0	1.0	0

Table 10. Contd

Date	Day of Year	Mode[1]	FACE + CONTROL Rep 1	Rep 2	Rep 3	Rep 4	FIZZ Irrig. Amount	CO_2 Time
			- - - - - - - - mm	- - - - - - -			mm	hr
22-Jul	204	I	10.7	11.4	11.2	11.3	11.1	3.9
23-Jul	205	I	10.7	11.4	11.2	11.3	11.1	3.9
24-Jul	206	I	10.7	11.4	11.2	11.3	11.1	3.9
25-Jul	207	I	10.7	11.4	11.2	11.3	11.1	3.9
26-Jul	208	I	10.7	11.4	11.2	11.3	11.1	3.9
27-Jul	209	I	10.7	11.4	11.2	11.3	11.1	3.9
28-Jul	210	I	10.7	9.5	8.8	7.0	9.3	1.8
29-Jul	211	I	10.7	9.5	8.8	7.0	9.3	1.8
30-Jul	212	R	8.6	8.6	8.6	8.6	8.6	0
31-Jul	213	I	10.7	9.5	8.8	7.0	9.3	1.8
01-Aug	214	I	11.0	11.5	12.4	12.7	13.3	4.6
02-Aug	215	I	11.0	11.5	12.4	12.7	13.3	4.6
02-Aug	215	R	5.1	5.1	5.1	5.1	5.1	0
03-Aug	216	I	11.0	11.5	12.4	12.7	13.3	4.6
04-Aug	217	I	9.3	9.2	8.6	8.9	8.5	3.0
05-Aug	218	I	9.3	9.2	8.6	8.9	8.5	3.0
05-Aug	218	R	1.0	1.0	1.0	1.0	1.0	0
06-Aug	219	I	9.3	9.2	8.6	8.9	8.5	3.0
07-Aug	220	I	9.3	9.2	8.6	8.9	8.5	3.0
08-Aug	221	I	9.3	9.2	8.6	8.9	8.5	3.0
09-Aug	222	I	9.3	9.2	8.6	8.9	8.5	3.0
10-Aug	223	I	9.3	9.2	8.6	8.9	8.5	3.0
11-Aug	224	I	9.2	9.6	9.6	9.7	10.0	3.6
12-Aug	225	I	9.2	9.6	9.6	9.7	10.0	3.6
13-Aug	226	I	9.2	9.6	9.6	9.7	10.0	3.6
14-Aug	227	I	9.2	9.6	9.6	9.7	10.0	3.6
15-Aug	228	I	9.2	9.6	9.6	9.7	10.0	3.6
16-Aug	229	I	9.2	9.6	9.6	9.7	10.0	3.6
17-Aug	230	I	9.2	9.6	9.6	9.7	10.0	3.6
18-Aug	231	I	12.0	11.4	12.1	12.6	11.4	4.0
19-Aug	232	I	12.0	11.4	12.1	12.6	11.4	4.0
20-Aug	233	I	12.0	11.4	12.1	12.6	11.4	4.0
21-Aug	234	I	12.0	11.4	12.1	12.6	11.4	4.0
21-Aug	234	R	7.1	7.1	7.1	7.1	7.1	0
22-Aug	235	I	12.0	11.4	12.1	12.6	11.4	4.0
23-Aug	236	I	12.0	11.4	12.1	12.6	11.4	4.0
24-Aug	237	I	12.0	11.4	12.1	12.6	11.4	4.0
25-Aug	238	I	7.0	7.2	6.9	5.9	8.1	2.8
26-Aug	239	I	7.0	7.2	6.9	5.9	8.1	2.8
27-Aug	240	I	7.0	7.2	6.9	5.9	8.1	2.8
28-Aug	241	I	7.0	7.2	6.9	5.9	8.1	2.8
29-Aug	242	R	7.9	7.9	7.9	7.9	7.9	0

Table 10. Contd

Date	Day of Year	Mode[1]	FACE + CONTROL Rep 1	Rep 2	Rep 3	Rep 4	FIZZ Irrig. Amount	CO_2 Time
			mm				mm	hr
29-Aug	242	I	7.0	7.2	6.9	5.9	8.1	2.8
30-Aug	243	R	2.8	2.8	2.8	2.8	2.8	0
30-Aug	243	I	7.0	7.2	6.9	5.9	8.1	2.8
31-Aug	244	I	7.0	7.2	6.9	5.9	8.7	2.0
01-Sep	245	I	7.4	7.5	7.2	7.4	7.4	0
02-Sep	246	I	7.4	7.5	7.2	7.4	7.4	0
03-Sep	247	I	7.4	7.5	7.2	7.4	7.4	0
04-Sep	248	I	7.4	7.5	7.2	7.4	7.4	0
05-Sep	249	I	7.4	7.5	7.2	7.4	7.4	9
06-Sep	250	I	7.4	7.5	7.2	7.4	7.4	0
07-Sep	251	I	7.4	7.5	7.2	7.4	7.4	0
08-Sep	252	I	7.4	7.5	7.2	7.4	7.4	0
09-Sep	253	I	7.4	7.5	7.2	7.4	7.4	0
		Totals	1232.1	1252.9	1220.0	1231.9	1241.8	230.4

[1] F = flood irrigation
I = drip irrigation
R = rain

Table 11. Nitrogen fertilizer[1] applications to the plots of the 1988 FIZZ/FACE experiment.

		FACE + CONTROL PLOTS								FIZZ Plots	
	Day of	Rep 1		Rep 2		Rep 3		Rep 4		(All Reps)	
Date	Year	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-	NH_4^+	NO_3^-
		kg N/ha									
21-Apr[2]	112	26.92	-	26.92	-	26.92	-	26.92	-	26.92	-
26-May[3]	147	150.04	-	150.04	-	150.04	-	150.04	-	150.04	-
10-Jun	162	15.56	4.97	-	-	-	-	-	-	-	-
14-Jun	166	-	-	15.18	4.85	-	-	-	-		
15-Jun	167	-	-	-	-	15.03	4.80	15.44	4.93	15.30	4.88
27-Jun	179	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
30-Jun	182	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
05-Jul	187	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
08-Jul	190	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
13-Jul	195	15.10	4.82	15.06	4.81	15.15	4.85	15.15	4.84	15.02	4.80
20-Jul	202	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.85	15.02	4.80
27-Jul	209	15.10	4.82	15.06	4.81	8.42	2.69	15.15	4.84	15.02	4.80
29-Jul	211					6.04[4]					
09-Aug	222	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
16-Aug	229	15.10	4.82	15.06	4.81	15.16	4.85	15.15	4.84	15.02	4.80
TOTALS		328.40	48.40	327.65	48.16	327.75	46.26	328.71	48.49	327.40	48.10
TOTAL N		376.80		375.80		374.00		377.20		375.57	

1 Except for 21 April and 26 May, the fertilizer was urea-ammonium nitrate solution (32-0-0) (from Pure Grow Co., West Sacramento, CA) containing 7.75% ammoniacal nitrogen, 7.75% nitrate nitrogen and 16.5% urea nitrogen injected into the drip irrigation system.

2 Ammonium sulfate-phosphate (16-20-0) broadcast before planting.

3 Urea (46-0-0) applied as a sidedress.

4 Ran out of urea-ammonium nitrate on 27 July, so urea was added alone on 29 July.

Table 12. Mean CO_2 concentrations and associated standard deviations at the 75% plant height from 28 July through 27 August for the 1988 FACE experiment at Phoenix, Arizona. The CO_2 was applied from 12:00 to 16:00 each day.

Averaging Interval	Rep		Control	FACE
			- - - - μmol mol^{-1} - - - -	
13:00-14:00				
	1		346 ± 21	498 ± 132
	2		--	578 ± 211
	3		--	424 ± 89
	4		--	458 ± 133
		Average	346 ± 21	489 ± 141
Daytime:				
	1		361 ± 36	402 ± 100
	2		--	428 ± 150
	3		--	380 ± 65
	4		--	389 ± 93
		Average	361 ± 36	400 ± 102
Nighttime:				
	1		395 ± 38	398 ± 40
	2		--	400 ± 37
	3		--	404 ± 40
	4		--	395 ± 36
		Average	395 ± 38	399 ± 38
Whole (24 hr) day:				
	1		376 ± 41	400 ± 80
	2		--	415 ± 116
	3		--	391 ± 57
	4		--	391 ± 73
		Average	376 ± 41	399 ± 82

Table 13. Mean CO_2 concentrations and standard errors of means, as measured with a LI-COR 6200 Portable Photosynthesis System on 11 days during the growing season of the 1988 FIZZ/FACE experiment while the FACE plots were being enriched. The means are averages over reps and day-of-year. Day-of-year was a significant factor as was the CO_2 x day-of-year interaction.

Leaf No.	CO_2 Control	FIZZ	FACE	±SEM	n
	- - - - - - - - μmol mol^{-1}			- - - - - -	
1	336	333	374	6	44
2	336	336	354	6	44
3	333	331	358	6	44
Means over leaves	335	333	362	2	132

Table 14. Final harvest data from the open-field release (FIZZ-FACE) experiment. Data are averages of 5 m^2 harvested on 12 September (day 256) 1988 for each of the four replications.

Treatments:	Control (C)				FIZZ (Z)				FACE (A)			
Item \ Replicate:	I	II	III	IV	I	II	III	IV	I	II	III	IV
Plant Height[1] (cm)	95	103	123	111	114	103	124	111	127	122	111	130
Leaf Area Index[1]	2.69	5.01	3.88	4.65	5.23	4.10	5.16	4.04	3.95	4.22	4.01	4.14
Top Dry Wt. (g/m^2)	1063	1002	813	1051	1011	928	1073	1031	1053	1152	741	1068
Root Dry Wt. (g/m^2)	-	-	-	-	-	-	-	-	-	-	-	-
Avg. Top Dry Wt. (g/m^2)		982				1011				1004		
Rel. CO_2 Effect		1.00				1.03				1.02		
Lint Wt.[2] (g/m^2)	54	62	37	63	23	48	26	94	27	42	16	67
Seet Wt.[2] (g/m^2)	91	104	64	104	40	82	46	158	47	72	27	114
% Lint	37	37	37	38	37	37	36	37	37	37	37	37
Open Bolls (No./m^2)	48	52	33	50	26	39	24	69	22	38	18	55
Green Bolls (No./m^2)	107	102	89	100	119	89	112	87	101	109	101	85
Total Bolls (No./m^2)	154	153	122	150	145	128	136	156	124	146	118	140
Seed Cotton[3] (g/m^2)	405	428	321	431	296	366	342	506	341	377	240	403
Average (g/m^2)		396				378				340		
Rel. CO_2 Effect		1.00				0.95				0.86		
Seed Index (g/100 seeds)	7.6	9.1	7.3	8.5	6.1	8.3	7.1	8.2	8.0	8.2	6.2	8.5
Harvest Index[4]	38	43	40	41	29	39	32	49	32	33	32	38

1 On 24 Aug 1988
2 Does not include weight of green, unopened bolls at time of harvest.
3 Includes estimate of green boll contribution with assumption green bolls will yield 0.8 as much as the present open bolls.
4 (Seed cotton weight/top dry weight) x 100.

Table 15. Average daily flowering, boll-set, and boll retention by weeks through the season for the 1988 FIZZ/FACE experiment.

Day of Year Interval	Mid-interval Date	Flowering[1]			Boll set[2]			Boll Retention[3]		
		Cont.	FIZZ	FACE	Cont.	FIZZ	FACE	Cont.	FIZZ	FACE
		- - - - - No. m^{-2}	day^{-1} - - - - - - -					- - - - % - - -		
178-184	30 Jun	0.7	0.6	0.3	0.3	0.3	0.2	56	47	20
185-191	7 Jul	1.7	1.9	1.5	0.9	0.7	0.4	26	40	15
192-198	14 Jul	2.2	2.5	1.4	1.7	1.5	0.9	60	54	32
199-205	21 Jul	4.3	4.0	4.0	2.5	1.9	1.9	37	38	45
206-212	28 Jul	7.0	7.2	6.6	2.6	2.6	2.7	38	34	40
213-219	4 Aug	6.1	6.0	6.4	1.8	2.1	2.1	25	29	30
220-226	11 Aug	4.9	5.8	5.6	3.0	3.1	2.7	57	54	50
277-233	18 Aug	4.6	4.8	5.2	2.5	2.8	2.9	57	30	55
234-240	25 Aug	4.1	4.4	4.8	1.7	2.2	2.1	38	50	43

[1] Total number of flowers tagged averaged over 5 working days and 4 replication

[2] Total number of bolls set per week averaged over 4 replications and 7 days p week.

[3] Average of the individual boll retention percentages for 5 days each week a for 4 replicate plots.

Table 16. Biomass and seed cotton yield data from three years of the FIZZ/FACE experiment. The numbers in parenthesis are the relative effects of the CO_2 treatments.

CO_2	Rep/Year:	Biomass (Top Dry Weight) 1986	1987	1988	Avg.	Seed Cotton Yield (Lint + Seed) 1986	1987	1988	Avg.
		- - - - - g m^{-2}				- - - - - g m^{-2}			
Control	I	705	493	1063		391	307	405	
	II	969	473	1002		522	302	428	
	III	441	401	813		246	312	321	
	IV	624	466	1051		426	377	431	
	Avg.	685	458	982	708 (1.00)	396	325	396	372 (1.00)
FIZZ	I	743	535	1011		419	394	296	
	II	740	608	928		414	419	366	
	III	503	534	1073		282	382	342	
	IV	788	657	1031		479	382	506	
	Avg.	694	584	1011	763 (1.08)	399	394	378	390 (1.05)
FACE	I	851	643	1053		439	435	341	
	II	793	553	1152		433	394	377	
	III	642	508	741		356	327	240	
	IV	856	647	1068		501	422	403	
	Avg.	786	588	1004	792 (1.12)	432	395	340	389 (1.05)
	Avg. by year	721	543	999		409	371	371	

Table 17. Rough comparison of the value to a grower of increased yield of seed cotton and the costs for CO_2 of the FIZZ and FACE treatments for three years.

	TREATMENT							
	FIZZ				FACE			
	Yield		CO_2		Yield		CO_2	
Year	Amount of Increase kg/ha	Value[1] $/ha	Amount Used Mg/ha	Cost[2] $/ha	Amount of Increase kg/ha	Value[1] $/ha	Amount Used Mg/ha	Cost[2] $/ha
1986	30	40	33	5,280	360	475	420	67,200
1987	690	911	24	3,840	700	924	140	22,400
1988	-180	-238	16	2,560	-560	-739	140	22,400

[1] At $1.32/kg (60¢/lb) for seed cotton.

[2] At $160/Mg for CO_2 and does not include field distribution costs.

Table 18. Mean net photosynthesis and stomatal conductance observed on 11 days of the 1988 FIZZ/FACE experiment while the FACE plots were being enriched. The means are averages over 3 leaves per plot, 4 replicate plots, and 11 days. Means not followed by the same letter are significantly different at the 0.05 probability level using LSD after F test.

		CO_2		
Item	n	CONTROL	FIZZ	FACE
Net Photosynthesis ($\mu mol\ m^{-2}\ s^{-1}$)	132	28.1a	28.1a	29.1a
Stomatal conductance ($cm\ s^{-1}$)	132	2.89a	3.15a	2.90a

Table 19. Proposed format for presenting cotton harvest summary data.

FILEA: Measured Cotton Crop Harvest Summary Data

Description. FILEA is a small file which contains a summary of measured fi harvest data for the crop for a particular treatment averaged over replications. The following proposed format for cotton follows the IBSNAT form for maize, wheat, and soybean as closely as possible. The "X" for the init letter of variable names indicates experimentally observed data.

Variable Name	FORTRAN Format	Description
INSTE	A2	Code for institute ID.
SITEE	A2	Code for site ID.
YEAR	I2	Year number, last two digits
EXPTNO	I2	Experiment number
TRTNO	1X,I2	Treatment number
XLTYLD	1X,F7.0	Actual field-measured lint yield (dry weight basis, kg/ha). This is the yield attainable by hand harvesting. If the cotton was harvested by machine, then the data must first be corrected for "gin turnout" or "harvest efficency
XSDYLD	1X,F7.0	Actual field-measured seed yield (dry weight basis, kg/ha)
XSDWT	1X,F7.4	Measured seed dry weight (g/seed)
XBLSM	1X,F6.0	Field-measured boll number (bolls/m^2)
XSPB	1X,F4.0	Field-measured number of seeds per boll (seeds/boll)
XLAIMX	1X,F5.2	Maximum leaf area index during season (m^2/m
XBIOM	1X,F6.0	Field-measured above-ground dry biomass maturity (kg/ha)
XSTMBR	1X,F6.0	Field-measured stem plus burr weight at maturity (kg/ha)
Start line 2		
XSDTN	F6.2	Measured nitrogen concentration in seed at maturity (%)
XTOTNP	1X,F5.1	Measured total crop nitrogen content at maturity (kg/ha)
XAPTNP	1X,F5.1	Measured nitrogen content of stems plus burrs plus lint at maturity (kg/ha)
XSDN	1X,F5.1	Measured nitrogen content of seed at maturity (kg/ha)

Table 20. Proposed format for presenting intermediate cotton growth data

FILEB: Measured Cotton Intermediate Growth Data (for graphics)

Description. FILEB contains observed crop growth data obtained at intermediate days during the growing season. Data for all treatments of an experiment are stored in one file. The first line is header information which identifies the source of the data followed by days of year at which emergence, first square, and first flower occurred. On the second line, the first variable identifies the number of state variables for which there are matching field data, and the rest of the variables on this line are pointers which indicate the state variable for each column of data. Starting with the third line, there is one line of data for each observation date recorded in the minimum data set (MDS). Replication data for each treatment can be included by using a different line of data for each rep. A "-1" on the line immediately following a data line indicates the end of data for a specific treatment. The "X" or "J" for the first letter of the variable names indicates experimentally observed data.

Variable Name	FORTRAN Format	Description
Line 1:		
[Header]	* or 2A2,2I2, 1X,I2	ID codes for institute, site, year, experiment no., treatment no.
JEMRGD	* or 1X,I3	Day of emergence which is the day that 50% of the plants emerge from the soil (day of year)
JSQRJD	* or 1X,I3	Day of first square which is the day of year that 50% of the plants in the field displayed their first square (day of year)
JFLRJD	* or 1X,I3	Day of first flower which is the day of year that 50% of the plants in the field displayed their first flower (day of year)

Line 2:

NOVAR	* or I3	No. of state variables for which there are matching field data
NV(I),I=1,NOVAR	* or (NOVAR)I3	Pointer which indicates state variable number for each column of data

Line 3 and beyond:

JDOY()	* or I3	Day of Year (Julian)
NV(1) or XPLTHT()	* or F5.0	Plant height (cm)
NV(2) or XLAI()	* or F5.2	Leaf Area Index (m^2/m^2)
NV(3) or JNNODM()	* or I5	No. nodes/m^2
NV(4) or JNSQRM()	* or I4	No. squares/m^2
NV(5) or JNFLWM()	* or I4	No. flowers/m^2
NV(6) or JNGBLM()	* or I4	No. green bolls/m^2
NV(7) or JNMBLM()	* or I4	No. open mature bolls/m^2
NV(8) or JNABSM()	* or I5	No. abscised sites/m^2
NV(9) or XWLEFH()	* or F7.1	Dry leaf weight (kg/ha)
NV(10) or XWSTMH()	* or F7.1	Dry stem weight (kg/ha)
NV(11) or XWROTH()	* or F7.1	Dry root weight (kg/ha)
NV(12) or XWGBLH()	* or F7.1	Dry green boll weight (kg/ha)
NV(13) or XWMBLH()	* or F7.1	Dry mature boll weight (kg/ha)
NV(14) or XWLINT()	* or F7.1	Dry lint weight (kg/ha)
NV(15) or XWSEED()	* or F7.1	Dry seed weight (kg/ha)
NV(16) or XWBURR()	* or F7.1	Dry burr weight (kg/ha)

---

* Format uses one or more spaces to separate one variable from the next.

Table 21. Proposed standard form for recording cotton growth data.

FORM R-2

Growth Analysis, Harvest, and Final Yield Components for Cotton

				Number per m^2					
Date dd/mm/yy	Plot	Ht. cm (1)	LAI m^2/m^2 (2)	nodes (3)	squars (4)	flowrs (5)	green bolls (6)	mature bolls (7)	abscis site (8)
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									

		Biomass (kg/ha)							
Date dd/mm/yy	Plot	leaves (9)	stems (10)	roots (11)	green bolls (12)	mature bolls (13)	lint (14)	seed (15)	burrs (16)
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									
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__/__/__									
__/__/__									
__/__/__									
__/__/__									
__/__/__									

Table 22. Standard CO_2 database form for recording data extracted from the literature about CO_2 effects on plants.

CO_2 EXPERIMENT DATABASE Record No._____

Reference______________________________ Location_______________

Species-Common________________________ Cultivar_________________

Scientific_________________________ Photosyn____ Crop Type____

Season_____ CO_2 Exposure Method__ Age-Yield__ Air Plut_____,_____,_____

	Light μmol m^{-2} s^{-1}	Temp C	Rel Hum %	Irrig % of PE	Salt dS/m	Nutr mmol/L	Air Pol μL/L
Minimum		N_____	D_____	_____		N_____ P_____	_____
Maximum	_____	D_____ V_____	N_____		_____		_____
Regime (H,M,L)	__	__	__	__	__	__	__
Interaction (t,f)	_	_	_	_	_	_	_

	CO_2 CONC μL/L	CO_2 CON-TROL	YIELD Abs	YIELD Rel	BIOMASS Abs	BIOMASS Rel	LEAF CONDUCTANCE Abs	LEAF CONDUCTANCE Rel	LEAF TRANSPRATN Abs	LEAF TRANSPRATN Rel	HRVST INDEX Abs
Units:			_____		_____		_____		_____		
1	_____	__	_____	_____	_____	_____	_____	_____	_____	_____	_____
2	_____	__	_____	_____	_____	_____	_____	_____	_____	_____	_____
3	_____	__	_____	_____	_____	_____	_____	_____	_____	_____	_____
4	_____	__	_____	_____	_____	_____	_____	_____	_____	_____	_____
5	_____	__	_____	_____	_____	_____	_____	_____	_____	_____	_____

	C/N RATIO Abs	CARBON EXCHANGE RATE Short-Term Abs	CARBON EXCHANGE RATE Short-Term Rel	CARBON EXCHANGE RATE Long-Term Abs	CARBON EXCHANGE RATE Long-Term Rel	NET ASSIMILATION RATE Short-Term Abs	NET ASSIMILATION RATE Short-Term Rel	NET ASSIMILATION RATE Long-Term Abs	NET ASSIMILATION RATE Long-Term Rel	RT/SHT RATIO Abs
Units:		_____		_____		_____		_____		
1	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
2	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
3	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
4	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____
5	_____	_____	_____	_____	_____	_____	_____	_____	_____	_____

Note:____

Table 23. Codes for classifying data in the CO_2 database.

CO_2 EXPERIMENT DATABASE CODES

Photosynthesis Type: C3, C4, CAM, or other

Crop Type:
- FIB - fiber
- FLB - flower/biomass (e.g. single-stem poinsettia with fixed flower no.)
- FLW - flower (number of flowers)
- FRT - fruit
- GRN - grain
- LEF - leaf or forage (non-legume)
- LGS - legume seed crops
- LGF - legume leaf or forage
- RT - root or tuber
- RUB - rubber
- SUC - succulent
- SUG - sugar

- AQU - aquatic
- HRB - herbaceous non-ag
- WOD - woody perennials

Season:
- W - winter
- SP - spring
- SM - summer
- F - fall
- W-SP - winter-spring
- SP-SM - spring-summer
- SM-F - summer-fall
- F-W - fall winter
- SP-W - spring-winter
- Y - whole year or longer

CO_2 Exposure Method:
- G - GREENHOUSE (Temperature controlled by heating and ventilation. Usually not CO_2-enriched during ventilation.)
- C - CONTROLLED ENVIRONMENT CHAMBERS (artificial light, temp, RH, CO_2 controlled)
- F - FIELD CONDITIONS (free-air carbon dioxide experiment, FACE)
- O - OPEN-TOP CHAMBERS
- S - SUNLIT CONTROLLED ENVIRONMENT CHAMBERS (temp controlled at set point by refrigeration, RH may or may not be controlled. SPAR units.)
- T - TRACKING SUNLIT CHAMBERS (like S except temp set to track outside temperature, rather than at set point.)
- U - UNVENTILATED, temperature-controlled, high-humidity greenhouse.
- V - VENTILATED GREENHOUSE (temp, RH made as close as possible to outside conditions by high ventilation on the order of 4 air changes per minute.)
- W - WIND BREAK (tall vegetation, snowfence etc.)

Table 23. Contd

Age-Yield:
- Y - mature - harvested for agricultural yield
- S - seedling or sapling - harvested for biomass
- B - mature plants harvested for biomass

Air Pollutants: ETHYL for ethylene, NO, NO2, NOX, O3, SO2

Regimes:

Item	Low	Medium	High
Light (μmol m^{-2} s^{-1})	< 600 winter		> 1200 summer
Temp. of Air, Avg. Daily (C)	< 15		> 30
Relative Humidity (%)	< 25		> 75
Irrigation (% of Potential Evapotranspiration)	< 70		> 95
Salinity (dS/m = mmho/cm = approx. 640 ppm)	< 0.75		> 2.25
Nutrients (% of Hoagland = 30 mmole/L = 420 ppm for N 2 mmole/L = 62 ppm for P)	< 25		> 100
Air pollution (% of standards ethylene = 0.025 μL/L . NO = 0.25 μL/L NO2 = 0.25 μL/L NOx = 0.25 μL/L SO2 = 0.25 μL/L O3 = 0.25 μL/L)	< 50		> 100

CO_2 Exposure Control:
- C - CO_2 controlled Continuously (day and night) for 100% of life cycle
- D - CO_2 controlled for 100% of Daylight time of life cycle
- P - CO_2 controlled at specified levels for particular Portions or development stages of life cycle
- N - CO_2 Not controlled during ventilation, but generally was controlled during daylight hours when temperature not too high.
- E - "Enriched" without good control of concentration
- A - Ambient or reference treatment (300-400 μL of CO_2/L of air)

Table 23. Contd

Short-term Carbon Exchange Rate (Net Photosynthesis):
Measurements of CER made on plants grown at control level of CO_2 and measured at elevated CO_2.

Long-term Carbon Exchange Rate (Net Photosynthesis):
Measurements of CER on plants which have been growing for at least one week at the same level of CO_2 as that of the measurement.

Short-term Net Assimilation Rate:
NAR calculated for a growth interval of not longer than 2 weeks following a change of CO_2 level.

Long-term Net Assimilation Rate:
NAR calculated for a growth interval beginning two weeks or more following a change of CO_2 level.

Harvest Index:
Seed dry weight divided by total standing top dry weight (roots excluded) unless noted otherwise.

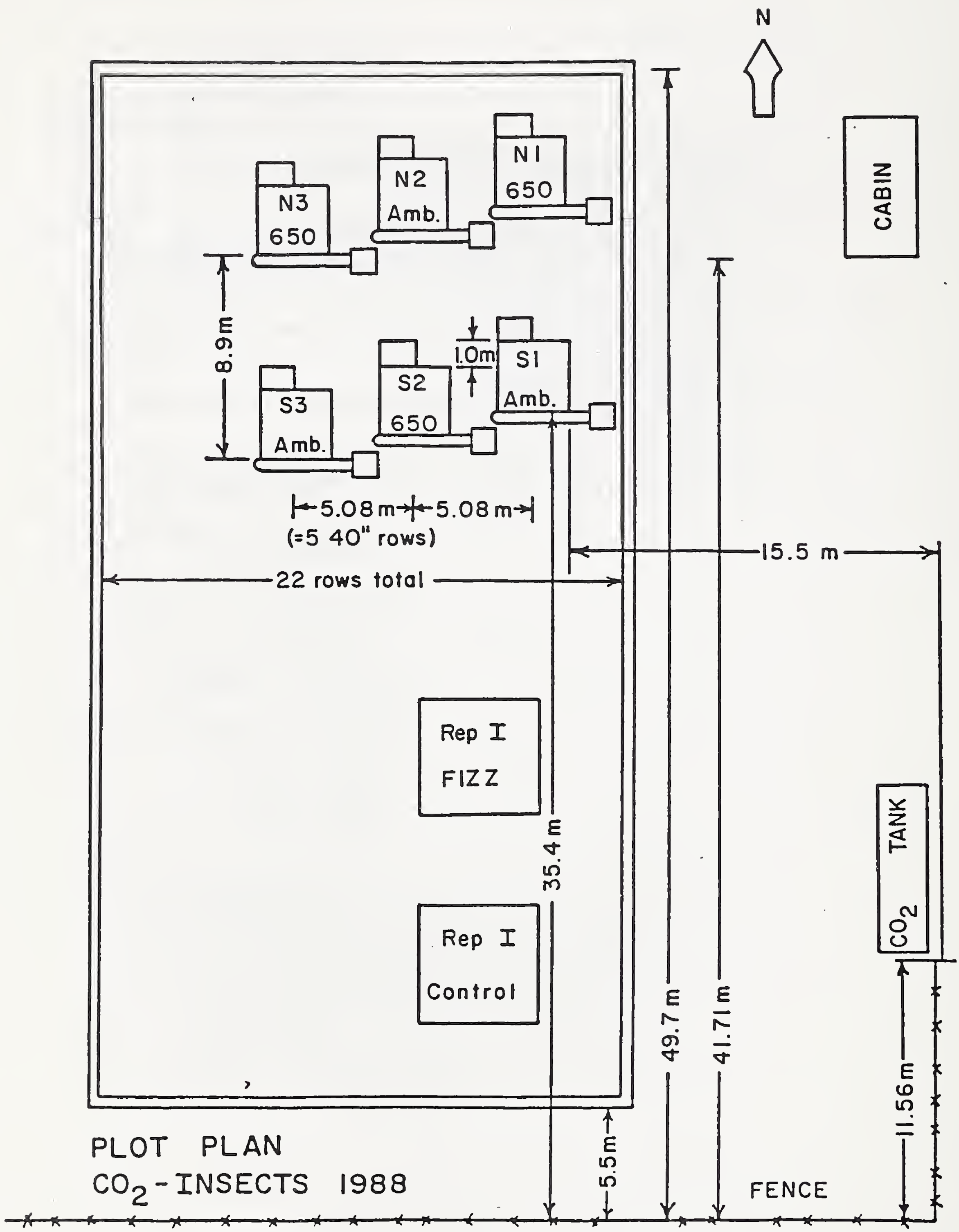


Fig. 1. Plot plan for the 1988 CO_2-INSECT experiment showing the arrangemen of the "screen-top" chamber plots with 3 replicates of ambient an 650 μmol CO_2 mol^{-1} treatments.

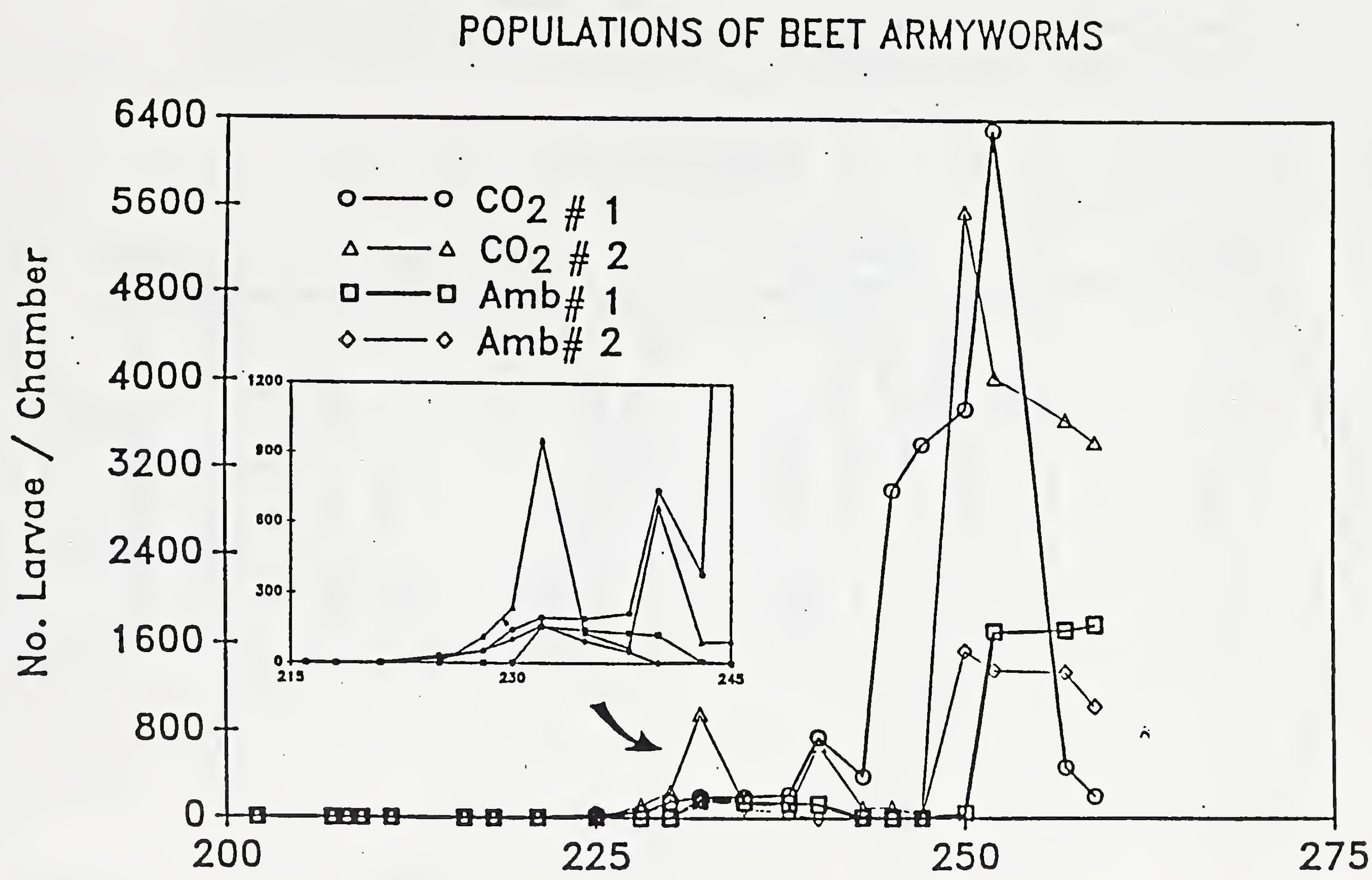


Fig. 2. Larval population of beet armyworm on CO_2 enriched cotton and on ambient control cotton (AMB) in screen-topped chambers (Note difference in scale of Y axis between Figures 2 and 3.

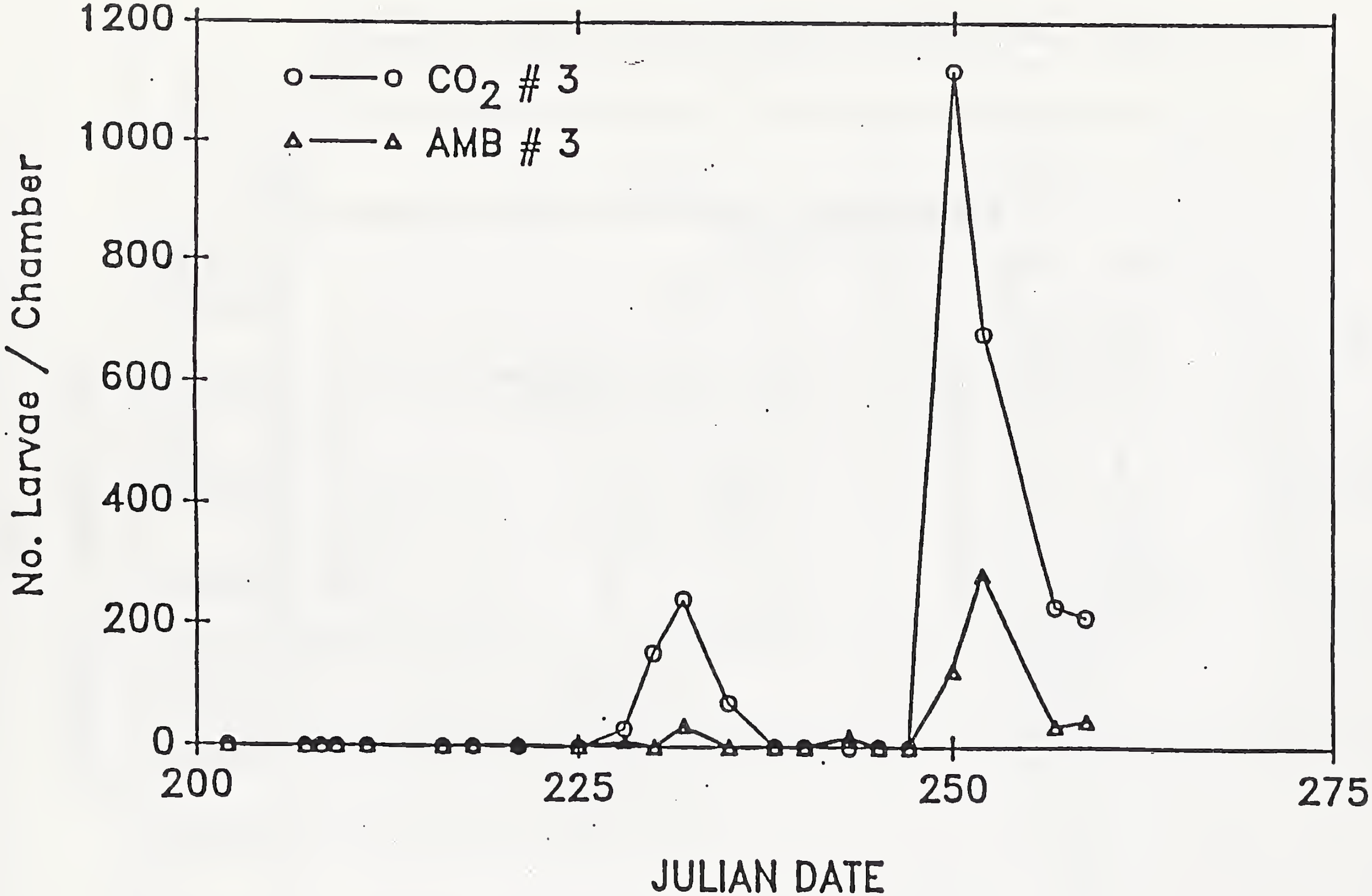


Fig. 3. Larval population of beet armyworm on CO_2 enriched cotton and on ambient control cotton (AMB) in screen-topped chambers (Note difference in scale of Y axis between Figures 2 and 3).

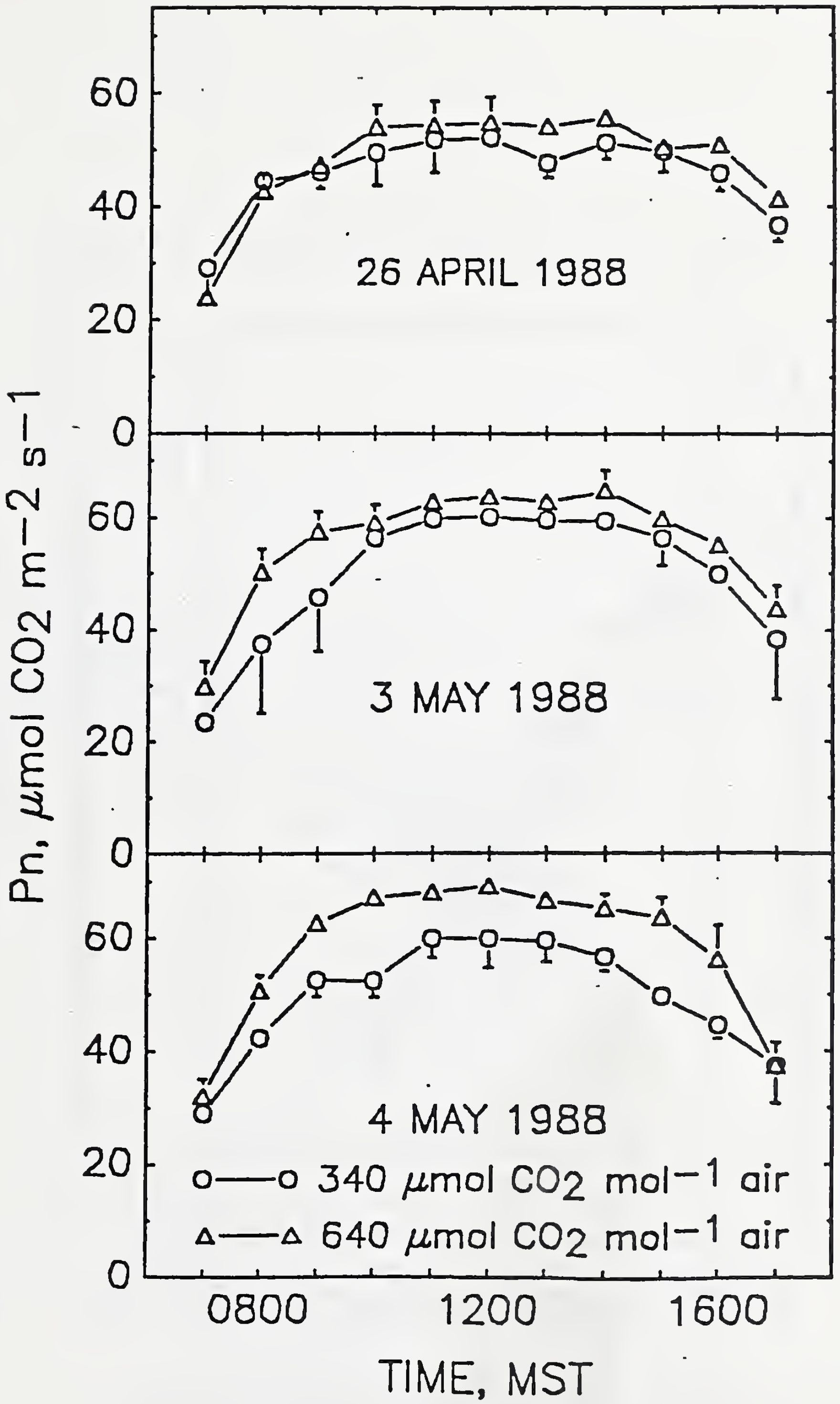


Fig. 4. Net photosynthesis (Pn) of single sorghum leaves in ambient CO_2 and 650 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 4 May 1988. Bars represent standard deviation.

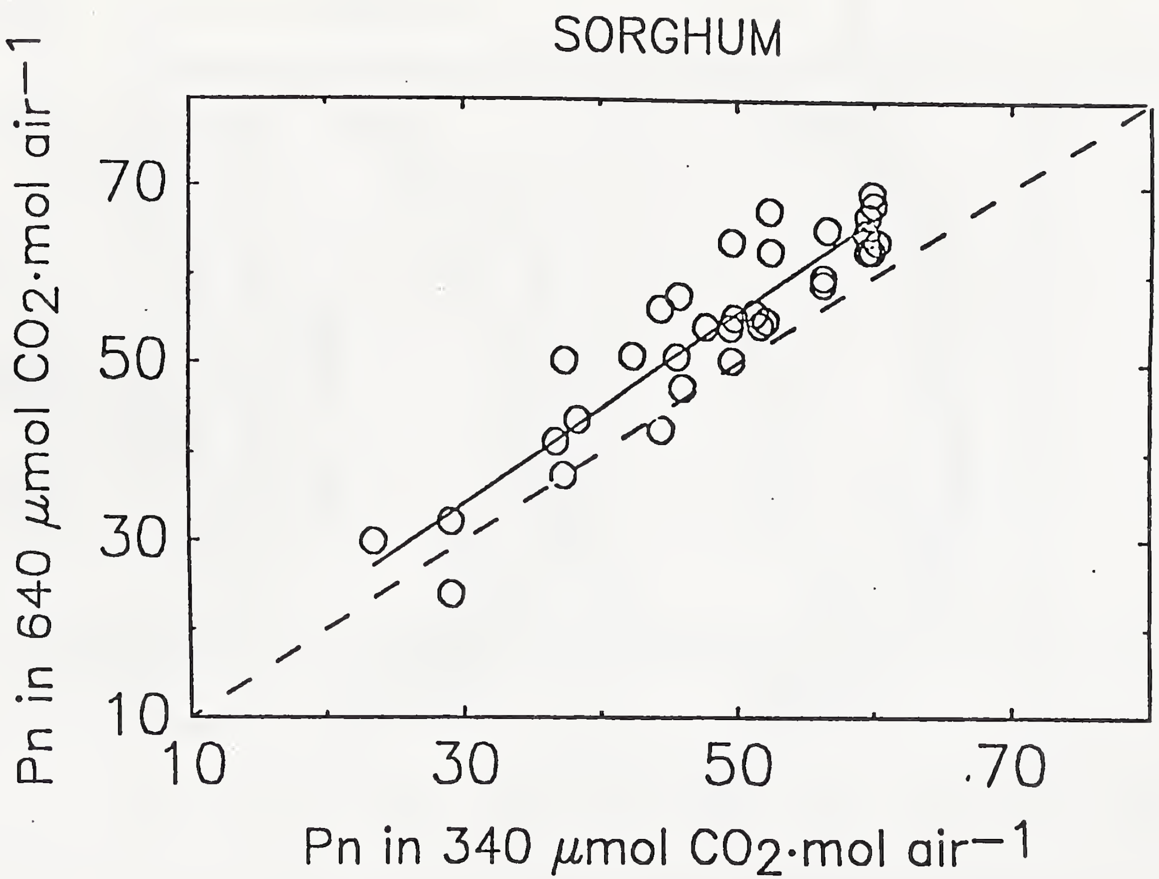


Fig. 5. Linear regression of the photosynthesis (Pn) of sorghum in 650 versus 350 μmol CO_2 mol air^{-1}. n = 33; slope = 1.08, not significantly different from 1.00 at $P < 0.05$.

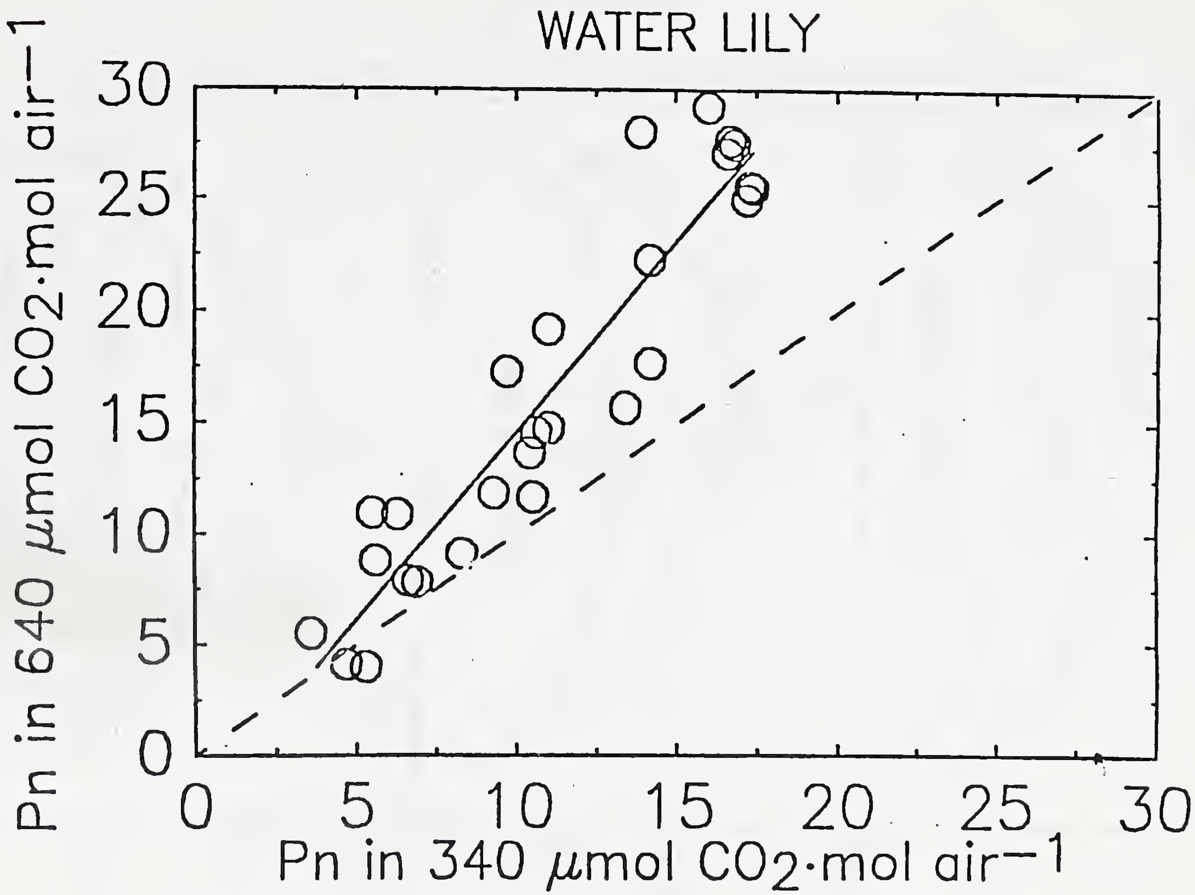


Fig. 6. Linear regression of net photosynthesis (Pn) of water lily in 650 versus 350 µmol mol air^{-1}. n = 27; slope = 1.70; significantly different from 1.00 at $P < 0.05$. From Allen et al., 1989.

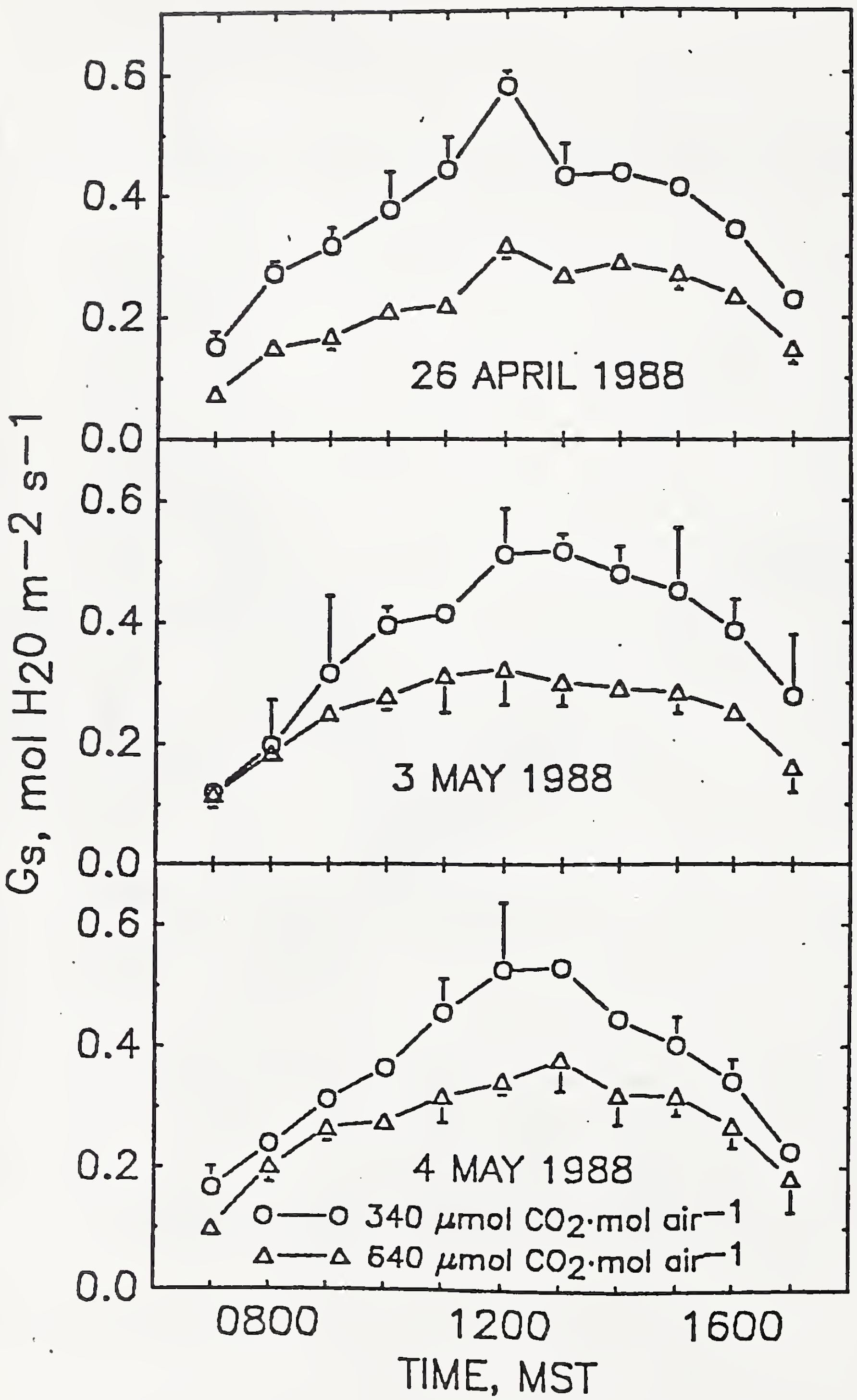


Fig. 7. Stomatal conductance of water vapor (Gs) of sorghum in ambient CO_2 and 650 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 4 May 1988. Bars represent standard deviation.

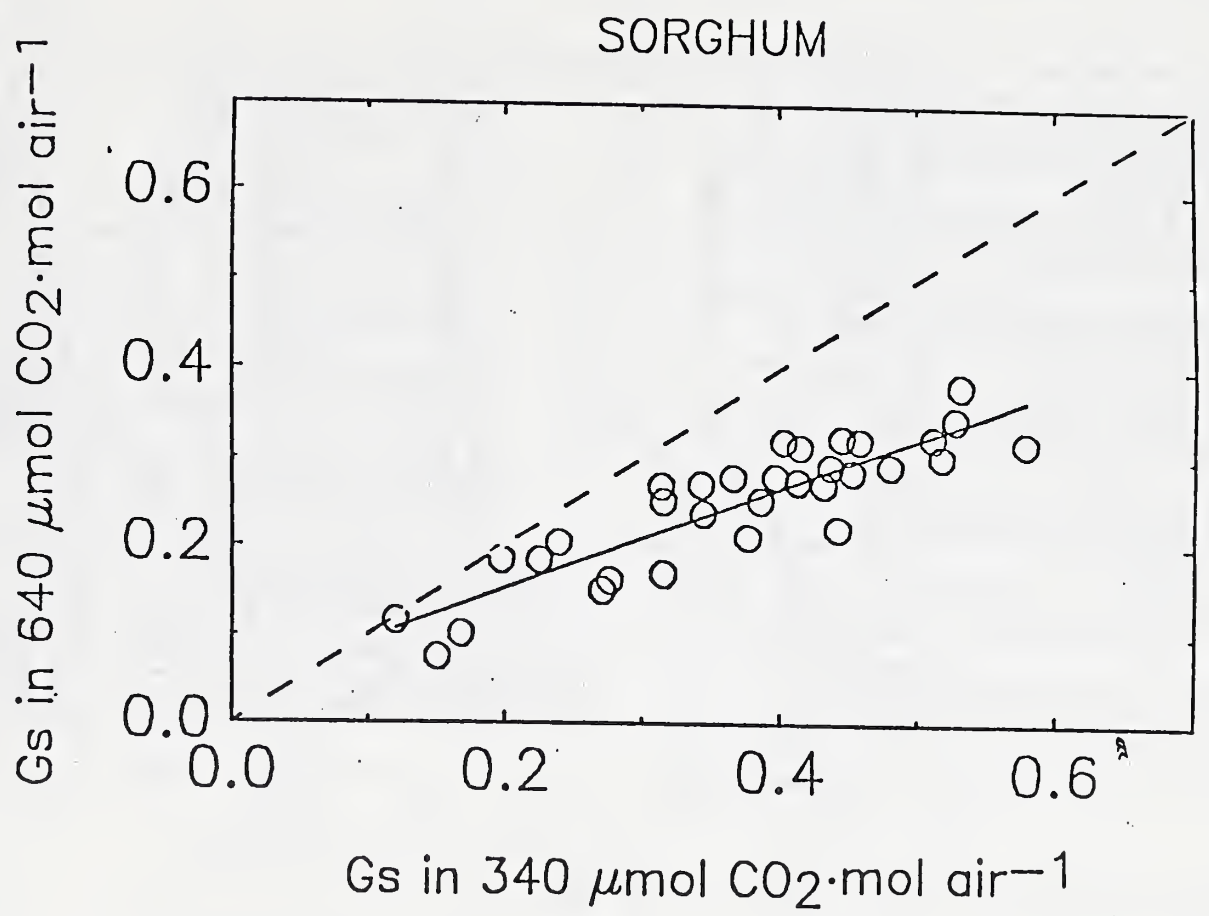


Fig. 8. Linear regression of stomatal conductance of water vapor (Gs) of sorghum in 650 versus 350 μmol CO_2 mol air^{-1}. n = 33; slope = 0.57, significantly different from 1.00 at $P < 0.05$.

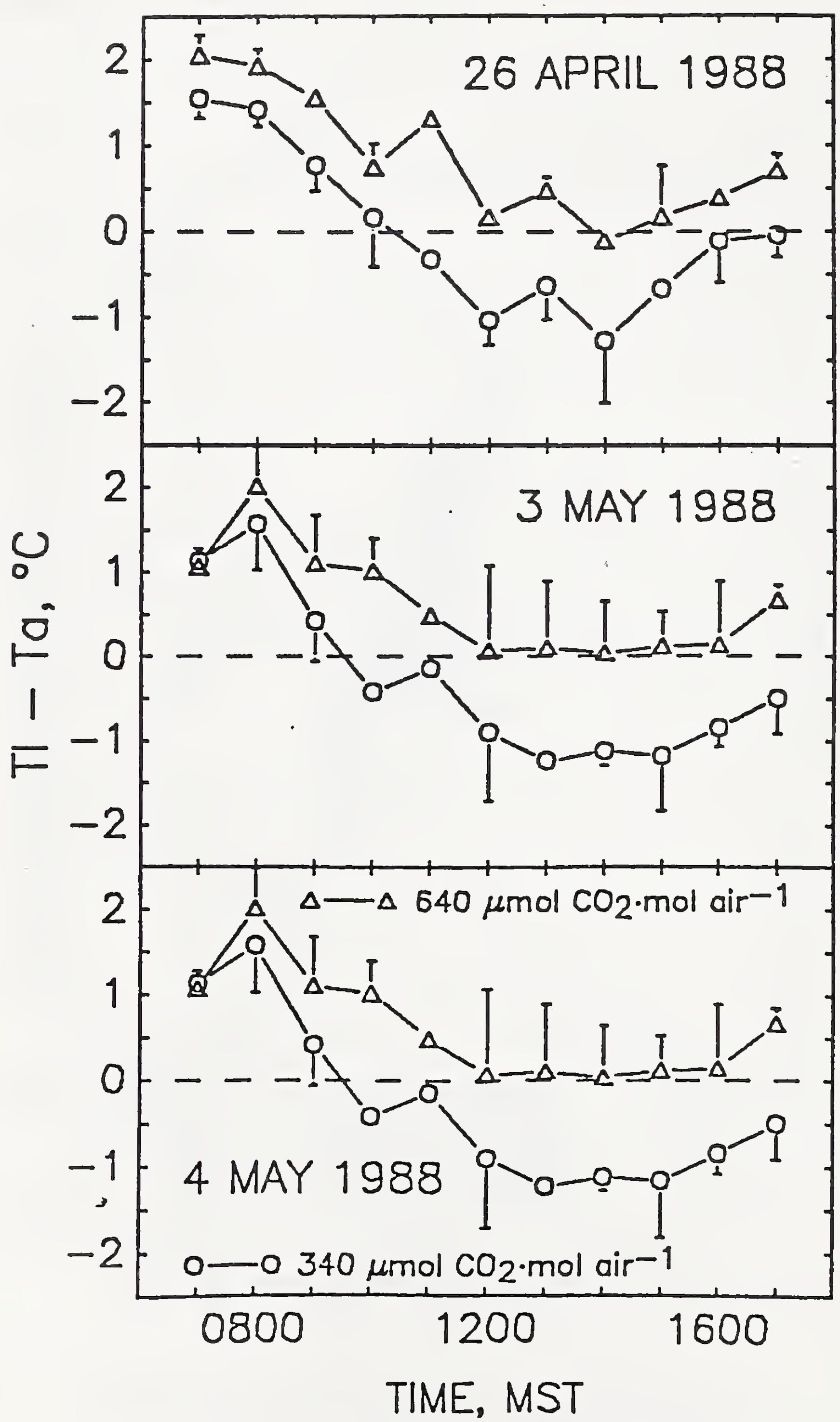
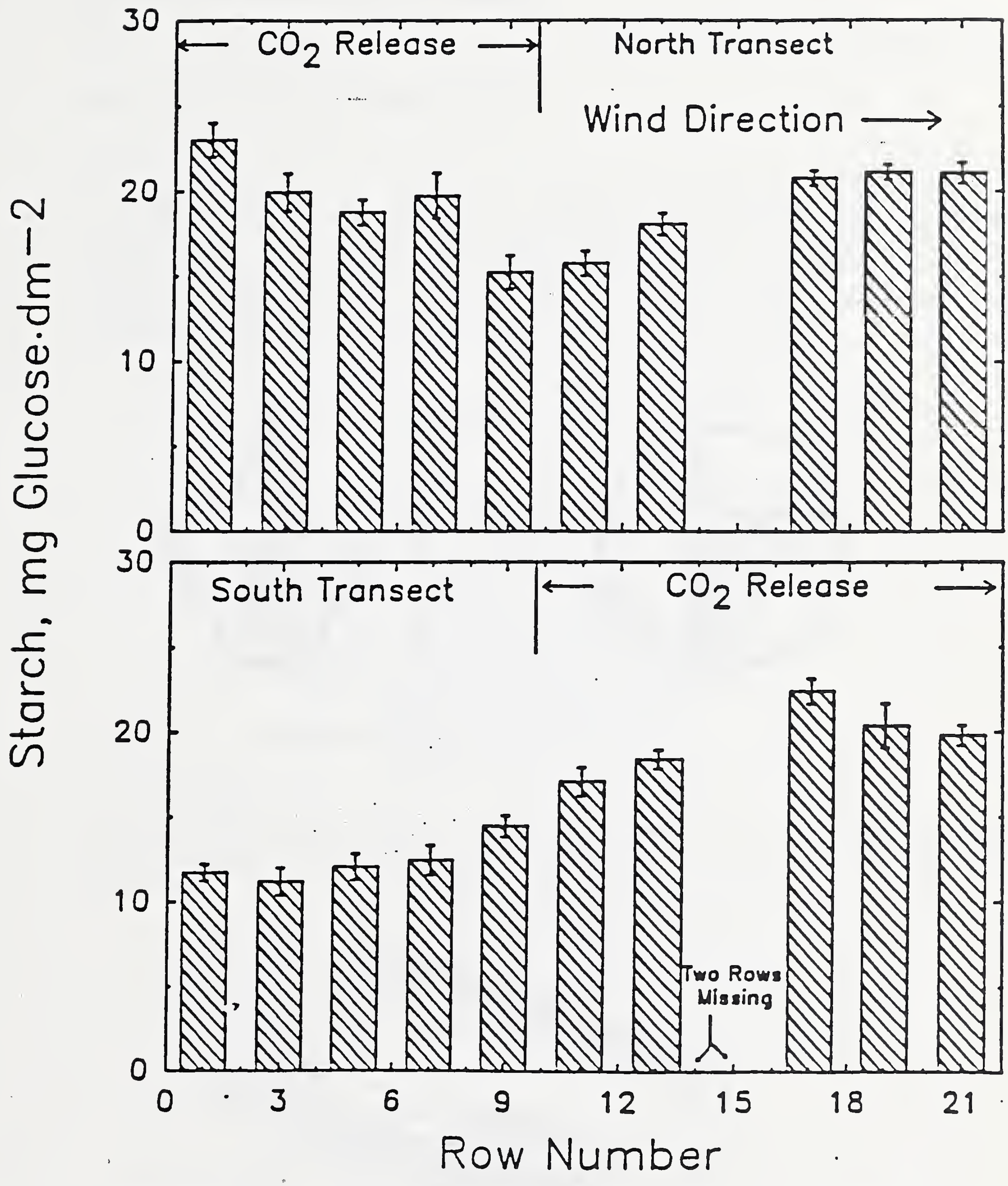


Fig. 9. Temperature differential between leaf and air (Tl -Ta) of sorghum in ambient CO_2 and 650 μmol CO_2 mol air^{-1} between 0700 and 1700 hr on 26 April, and 3 and 5 May 1988. Bars represent standard deviation.



g. 10. Leaf starch content of plants at the boundaries of the free-air CO_2 enrichment (FACE) plots, sampled about 2 pm on 28 July 1988. Leaves sampled were five nodes from the apex of the plant. Each bar represents the mean±SEM of ten samples per row, taken from plants along ten feet of row. Wind direction was from the west (left to right in the figures), so the "south" and "north" transects were across upwind and downwind boundaries, respectively.

TITLE: FLOW MEASUREMENT AND CONTROL

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001

FLOW CONTROL AND MEASUREMENT DEVICES:

Steel Jackgate:

A jackgate design was observed, resulting from one of the Pakistan projects for which we furnish a Cooperating Scientist, that may have special merit. It depends on tightly sandwiching a sliding steel gate between neoprene rubber strips so that a pry-bar is needed to lift or lower the plate, Figure 1. It makes the gate tamper resistant and relatively safe because it will not drop on toes or fingers.

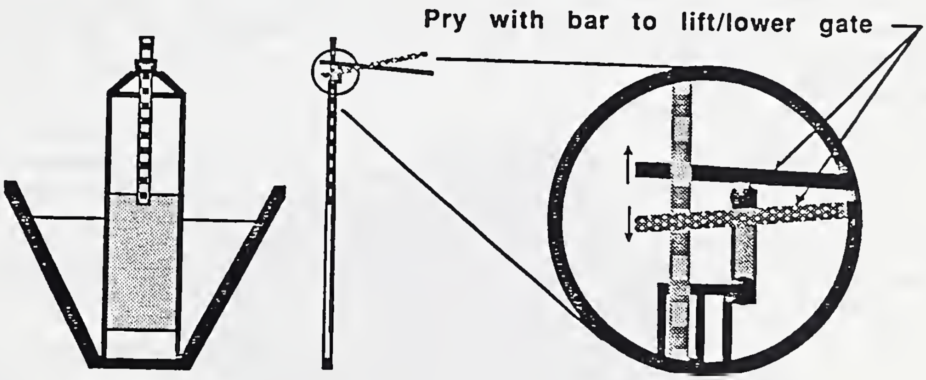


Figure 1. Jack-gate mechanism

Canal Linings:

Pre-fabricated canal linings, constructed with flume sections built into them as shown diagrammatically in Figure 2, were also observed and discussed.

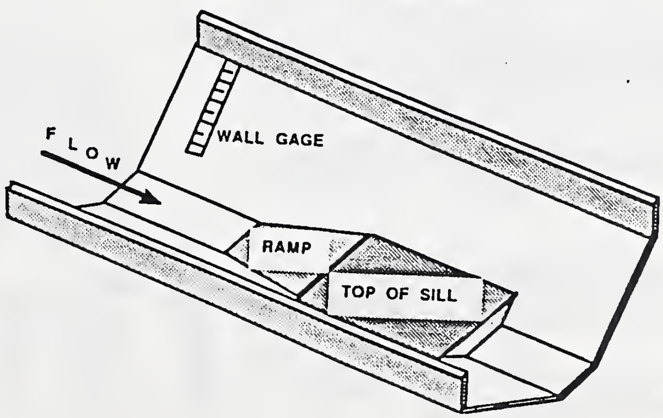


Figure 2. Pre-cast canal section lining with broad-crested weir

Flume Designs:

The evaluation of a new style of portable contraction section, designed and built by one of the assistant engineers at Lahore, was discussed. It was constructed of simple rectangular panels, somewhat as shown in Figure 3. Figure 4 illustrates the recommended version "B" that we discussed. The original version "A" is hard to hold in the flow because of the flowing water forces. The friction forces on the channel floor depend on the weight of the construction materials, since there are no down forces generated by the straight vertical slides. Version "B" has a flared bottom section and both have open bottoms that prevent buoyancy forces. The flared bottom should generate down forces that increase with depth of flow, because the water standing in the center of the contraction portion will be lower than the upstream flow depth. Two readout methods were discussed, the translocated stilling well method as shown and a staff gauge held on struts from the upstream end of the device, as illustrated with Version "A".

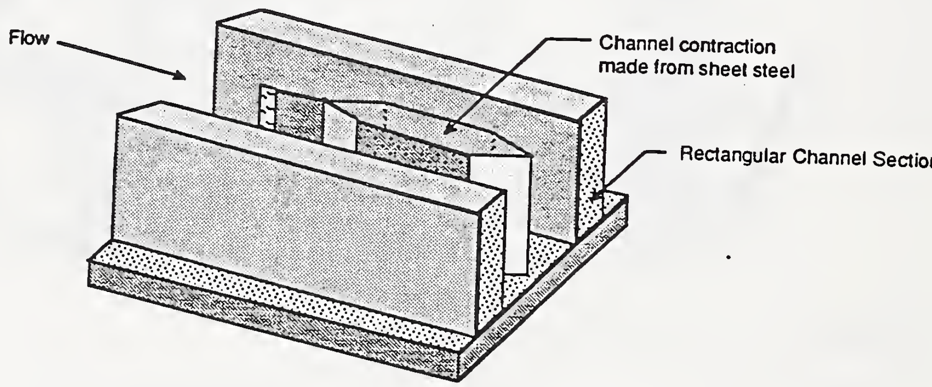


Figure 3. Portable centerline flume, Version "A"

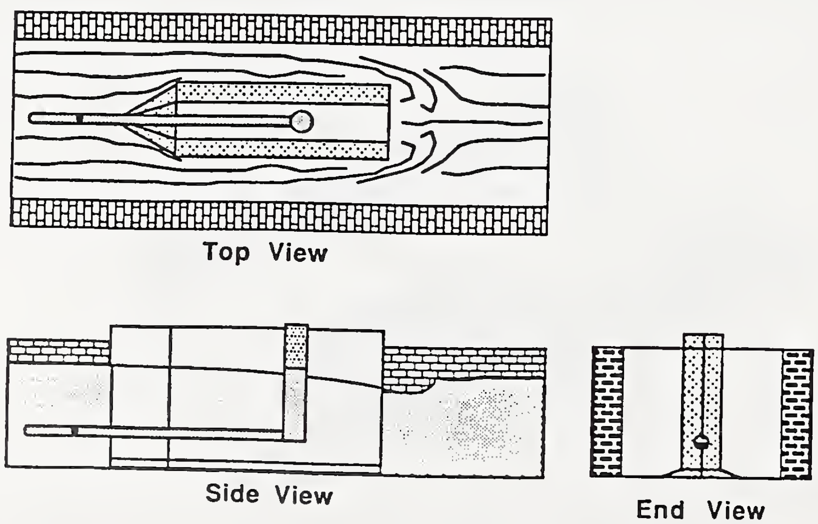


Figure 4. Portable centerline flume, Version "B"

During this writing, it was suggested that an alternate hold-down force could be generated by sealing the original bottom and opening an impact hole on the leading edge of the device that would overfill the interior and provide extra weight without having to construct the difficult flared bottom.

The portable contraction section is most practical for use in rectangular channels, and the calibration can be calculated with our computer model for flumes.

Concrete Slide gate:

Of other special interest was a commercial fabrication of an improved outlet, or "nakka", that was developed at Faisalabad, Figure 5. The operation of the rectangular sliding gate allows it to be safely opened under full canal pressures, a condition that was difficult using the older, round "nakkas" formerly developed through Colorado State University, that had to be forcibly lifted from their seats to open. The design which is manufactured for about R 60 in Faisalabad (less than $5), could possibly be built for use in the United States. With minor changes in the molding and reinforcing-steel fabrication patterns, it may be feasible to manufacture them at competitive pricing even under U.S. labor-cost conditions. They appear to be durable. The weight of less than about 45 Kg, for both the concrete sliding lid and the concrete frame seems attractive and small enough to not require on-site manufacturing.

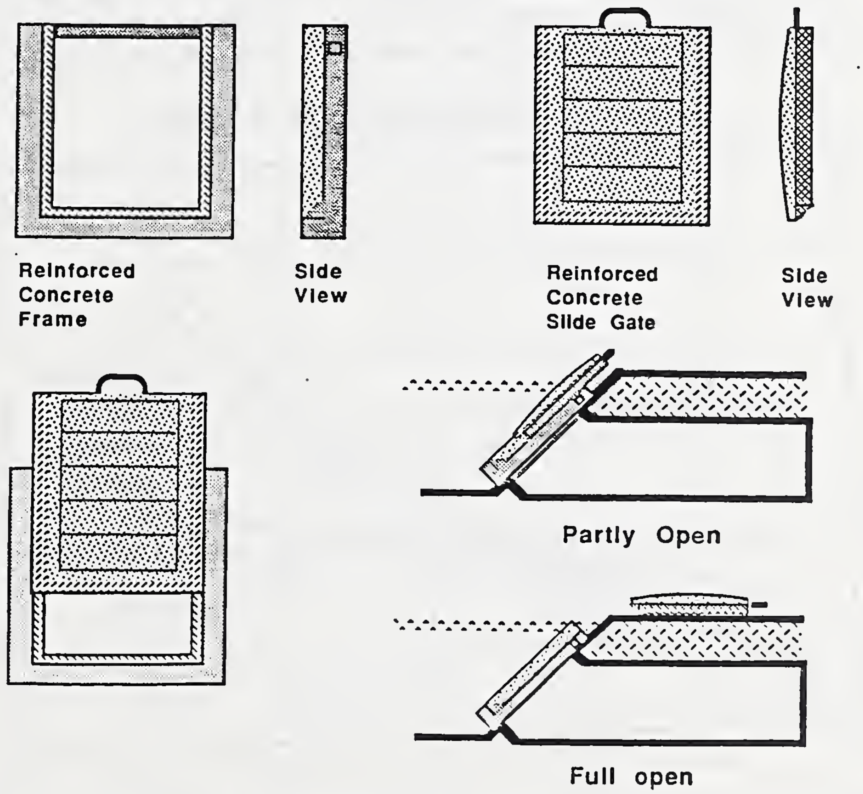


Figure 5. Concrete slidegate for port or small canal diversions.

The rectangular "NAKKA" canal gate would be usable in the U.S. The U.S. production costs would depend on mass-production techniques and a restructuring of reinforcing bars to reduce welding as presently used. Instead of welding, U.S. modifications would depend on simple bending of larger bar and single-piece reinforcements. Also, the U.S. version should have a concrete hand-hold with the reinforcing bar presently used covered with concrete, without an exposed reinforcing bar handle. Durability appears unlimited, particularly if the lifting handle is encased in concrete. The side seals are made with rounded lips that tend to wear to more water-tight sealing and which do not expose easily-chipped corners.

Palmer-Bowlus flumes:

A 15-inch Palmer-Bowlus flume was calibrated using the laboratory system. Profile data were collected as well as stage-discharge data. Also tested was the effect of entrance condition.

The profile data were observed and manually recorded in piezometer taps in the throat floor centerline at 1,3,6,10,20, and 30 cm from the outflow end of the flume throat. The discharges were obtained with the laboratory weigh-tank system.

Figure 6 shows that the published and model calibrations differ by about 1.5 to 2%. The published values indicate larger discharges relative to the model. The laboratory-measured values are about 5% less than the published ones at Hl/L= 0.1, and are nearly 6% higher at Hl/L = 0.75.

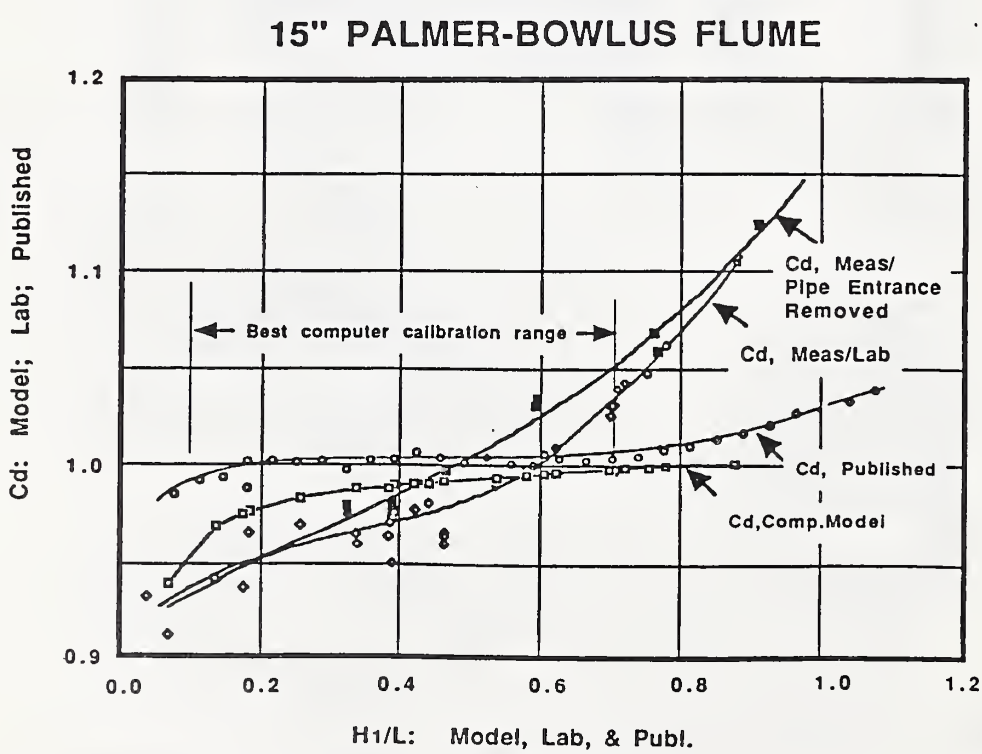


Figure 6. Palmer Bowlus Flume, Cd vs Hi/L

This can be explained, in part, by the laboratory observation of entry shock waves that suggests that the construction of the sidewall convergence is too abrupt. This would cause the most effect when the entrance flows were less than the elevation of the change in sideslope, which for this Palmer-Bowlus flume style is at a depth equal to ~3(D/4), or $H1/L = 0.4335$. Between about 0.5 and 0.75 the general effects noted for most short-throated flumes begin to show as over-discharge compared to the model expectations. This is probably the cause of the upturn in the curve beginning at about $H1/L = 0.5$.

The removal of the pipe entrance section caused surprisingly little shift in calibration, despite a significant degree of apparent turbulence that made direct surface measurements inaccurate. However, the stilling well appeared to maintain usable results.

<u>PERSONNEL</u>: Replogle, J. A.

TITLE: FLOWING FURROW INFILTROMETER TEST DATA

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001-00D

During the period 1983 to 1986, the SCS collected data on furrow infiltration rates with a flowing furrow infiltrometer developed jointly with the U.S. Water Conservation Lab. Some assistance was also provided on data collection procedures, data analysis, etc. In addition to infiltration rates and amounts, soil texture data was collected along with moisture contents and bulk densities. The furrow cross section, water depth and wetted perimeter were also measured. A trench across two furrows (wheel and non-wheel) was made for the bulk densities and moisture contents. Values were taken in each furrow and in the bed between them.

A considerable amount of the data was unusable for one reason or the other. The main causes were equipment failures and failure to record start times, etc. The infiltration data was analyzed and intake relations were plotted. Some data sets did not show a reasonable infiltration pattern and were discarded. The final data set is shown in Table 1. This data needs to be statistically analyzed. The intent of the analysis is to give better estimates of infiltration conditions based on soil textural/classification information. The textures of the soils studied is shown on the soil texture diagram in Figure 1.

SUMMARY:

Data on furrow infiltration was collected for a number of soils in Arizona with a flowing furrow infiltrometer in cooperation with the Soil Conservation Service. The data will be used to develop estimates of furrow infiltration from basic soil data; texture, moisture content, bulk density and wetted perimeter. This should aid in furrow irrigation design and in making recommendations to growers prior to observed irrigation events.

PERSONNEL: A.J. Clemmens, A.R. Dedrick

Table 1. Data from flowing furrow infiltrometer tests from 1983 to 1986.

OBS	DATE	FILE	SOIL	TEXTURE	ROW	SAND	SILT	CLAY	BDB	MB	K	A	WPR	WP	T	BD	M
1	08/16/83	1	Denure	ls	N	72.5	21	6.5	.	.	2.0890	0.6896	0.714	1.748	2.565	.	.
2	08/24/83	501	Gilman	fsl	W	55.5	32	12.5	.	15	2.2240	0.2910	0.670	1.422	7.517	1.70	.
3	08/25/83	2	Gilman	fsl	N	55.5	32	12.5	.	15	1.3860	0.4770	0.892	5.799	9.225	1.60	.
4	09/06/83	505	Mohall	scl	W	48.5	19	32.5	.	.	3.0280	0.2690	0.655	1.329	2.815	1.50	10
5	09/07/83	3	Rositas	lfs	N	78.5	12	9.5	1.60	.	4.7100	0.7753	0.683	1.509	0.810	1.30	10
6	09/07/83	502	Rositas	lfs	W	78.5	12	9.5	.	.	4.0090	0.4643	0.641	1.249	0.995	1.50	11
7	09/08/83	4	Contine	scl	N	52.5	26	21.5	.	13	3.7800	0.2931	0.659	1.354	1.213	1.50	.
8	09/09/83	503	Contine	scl	W	52.5	26	21.5	.	13	5.9400	0.2495	0.447	0.639	0.205	1.50	.
9	09/12/83	5	Mohall	sl	N	65.5	10	24.5	.	.	8.7660	0.5080	0.659	1.351	0.213	1.30	.
10	09/13/83	504	Mohall	sl	W	65.5	10	24.5	.	.	2.0320	0.4840	0.731	1.906	4.052	1.60	.
11	09/14/83	506	Gilman	l	W	44.0	32	24.0	.	.	1.7730	0.2770	0.656	1.337	18.864	1.60	22
12	09/15/83	6	Gilman	l	N	44.0	32	24.0	.	.	3.6160	0.3439	0.632	1.205	1.341	1.50	21
13	09/19/83	7	Avondale	c	XN	38.5	26	35.5	1.48	.	5.9260	0.7120	0.631	1.195	0.576	.	.
14	09/20/83	8	Avondale	c	N	38.5	26	35.5	1.48	.	5.0330	0.5480	0.635	1.218	0.658	1.40	.
15	09/21/83	9	Mohall	scl	XN	48.5	19	32.5	.	.	.	.	.	.	.	.	.
16	09/22/83	10	Agualt	l	N	49.5	32	18.5	.	15	1.6300	0.4510	0.684	1.517	7.319	1.30	19
17	09/23/83	507	Agualt	l	W	49.5	32	18.5	.	15	1.4370	0.4560	0.678	1.474	9.441	1.40	23
18	09/26/83	508	Coolige	sl	W	74.5	14	11.5	.	12	3.5890	0.6425	0.604	1.067	1.184	1.40	.
19	09/27/83	11	Coolige	sl	N	74.5	14	11.5	.	12	7.0300	0.4582	0.518	0.753	0.292	1.30	.
20	09/28/83	12	Mohall	scl	N	48.5	19	32.5	.	8	3.4090	0.3806	0.673	1.439	1.522	1.40	8
21	12/21/83	91	Mar?	scl	N	58.0	19	23.0	.	.	7.5170	0.7930	0.647	1.284	0.451	1.36	18
22	12/22/83	92	Mar?	scl	N	64.0	20	16.0	.	.	5.4920	0.5490	0.663	1.379	0.561	1.36	25
23	12/23/83	93	Mar?	scl	N	55.0	34	11.0	.	.	7.3720	0.5630	0.608	1.086	0.338	1.35	26
24	07/19/84	588	Gilman	l	N	45.0	40	15.0	1.39	14	4.3130	0.3670	.	0.900	0.814	1.42	18
25	07/20/84	509	Gilman	l	W	45.0	40	15.0	1.39	14	6.3600	0.4106	.	0.940	0.323	1.41	17
26	07/23/84	510	Glenbar	sicl	W	10.0	55	35.0	.	.	5.7600	0.5442	.	1.000	0.512	1.48	23
27	07/24/84	589	Glenbar	scl	N	10.0	55	35.0	.	.	5.3060	0.5946	.	1.300	0.622	1.29	23
28	07/25/84	511	Avondale	cl	W	30.0	35	40.0	1.40	12	2.9580	0.4662	.	0.960	1.910	1.55	18
29	07/27/84	13	Avondale	cl	N	30.0	35	40.0	1.40	12	6.1540	0.5480	0.633	1.050	0.456	1.22	15
30	07/30/84	590	Avondale	Sic	W	10.0	48	42.0	1.36	14	9.1900	0.4831	.	0.980	0.179	1.52	17
31	07/31/84	14	Avondale	Sic	N	10.0	48	42.0	1.36	14	11.8380	0.5904	.	0.960	0.159	1.37	22
32	08/02/84	591	Cashion	c	N	20.0	30	50.0	.	.	15.4240	0.4453	.	0.990	0.048	1.41	15
33	08/02/84	512	Cashion	c	W	20.0	30	50.0	.	.	4.8210	0.6687	.	0.940	0.756	1.51	14
34	08/07/84	592	Mohall	l	N	35.0	40	25.0	1.39	13	3.5340	0.5991	.	0.990	1.230	1.26	18
35	08/08/84	513	Mohall	l	W	35.0	40	25.0	1.39	13	3.0070	0.8911	.	0.940	1.377	1.53	16
36	09/05/84	593	Mohall	l	SN	35.0	40	25.0	1.73	.	2.2600	0.1158	0.569	0.923	.	.	.
37	09/06/84	514	Mohall	l	W	35.0	40	25.0	1.73	.	5.3020	0.5840	0.503	0.708	0.617	1.73	25

OBS	DATE	FILE	SOIL	TEXTURE	ROW	SAND	SILT	CLAY	BDB	MB	K	A	WPR	WP	T	BD	M
38	09/18/84	516	Glenbar	cl	W	40.0	25	35.0	1.50	.	2.3400	0.4295	0.711	1.719	3.484	1.53	25
39	09/19/84	594	Glenbar	cl	N	40.0	25	35.0	1.50	.	2.0300	0.3637	0.684	1.515	6.455	1.53	17
40	09/19/84	517	Gilman	cl	W	42.0	40	18.0	.	.	2.6470	0.4600	0.626	1.173	2.454	.	12
41	09/19/84	515	G	l	XXX	.	.	.	.	.	.	.	.	.	.	.	.
42	09/20/84	15	A	c	XXX	.	.	.	.	.	.	.	.	.	.	.	.
43	05/28/85	518	Gilman	l	W	37.0	41	22.0	1.39	12	1.3130	0.5720	0.611	1.098	7.011	1.41	19
44	05/30/85	16	Gilman	l	N	37.0	41	22.0	1.39	12	1.1968	0.8817	0.503	0.709	3.930	1.38	23
45	06/02/85	17	Marana	cl	N	33.0	40	27.0	1.50	22	2.3800	0.2514	0.662	1.370	7.887	1.37	28
46	06/02/85	519	Marana	cl	W	33.0	40	27.0	1.50	22	2.4700	0.1780	0.662	1.372	15.004	1.56	25
47	06/04/85	18	Casa_Gra	fsl	N	69.0	19	12.0	1.78	12	4.2240	0.3860	0.557	0.881	0.868	1.76	12
48	06/04/85	520	Casa_Gra	fsl	W	69.0	19	12.0	1.78	12	3.4250	0.3415	0.618	1.131	1.575	1.85	11
49	06/05/85	19	Casa_Gra	cl	N	45.0	23	32.0	1.49	15	8.1000	0.4200	0.598	1.040	0.186	1.67	18
50	06/05/85	521	Casa_Gra	cl	W	45.0	23	32.0	1.49	15	3.8340	0.4840	0.623	1.155	1.092	1.88	17
51	06/10/85	20	Gadsden	c	N	27	31	42	1.80	19.0	10.7000	0.1806	0.621	1.145	0.004	1.42	28.0
52	06/10/85	522	Gadsden	c	W	27	31	42	1.80	19.0	5.1550	0.3190	0.610	1.094	0.451	1.67	23.0
53	06/13/85	21	Mohave	scl	N	57	16	27	1.71	14.0	4.4900	0.4890	0.502	0.707	0.790	1.52	18.0
54	06/13/85	523	Mohave	scl	W	57	16	27	1.71	14.0	4.3430	0.4220	0.644	1.269	0.823	1.72	16.0
55	06/14/85	524	Vekol	c	W	28	30	42	1.51	30.0	8.7020	0.5789	0.638	1.233	0.261	1.49	19.0
56	06/14/85	22	Vekol	c	XN	28	30	42	1.51	30.0	2.1700	1.1430	0.708	1.694	.	.	.
57	06/17/85	23	Gila	l	N	32	47	21	1.42	16.0	1.0540	0.3510	0.728	1.871	44.689	1.49	19.0
58	06/17/85	525	Gila	l	XW	32	47	21	1.42	16.0	0.6190	1.1420	0.708	1.698	.	.	.
59	06/18/85	24	Sasco	l	N	38	37	25	1.24	14.0	5.1140	0.2960	0.539	0.820	0.436	1.59	13.0
60	06/18/85	526	Sasco	l	W	38	37	25	1.24	14.0	2.6100	0.5470	0.636	1.221	2.183	1.70	12.0
61	06/19/85	527	Aqua	l	W	37	46	17	1.56	15.0	2.9290	0.3486	0.743	2.028	2.445	1.68	19.0
62	06/20/85	25	Aqua	l	N	37	46	17	1.56	15.0	3.8250	0.5140	0.695	1.598	1.091	1.57	16.0
63	06/24/85	26	Gila	l	N	44	37	19	1.39	15.0	2.8090	0.4080	0.567	0.918	2.378	1.41	9.0
64	06/24/85	528	Gila	l	XW	44	37	19	.	.	.	.	.	.	.	.	.
65	06/25/85	529	Cogswell	cl	XW	30	35	35	1.52	18.0	1.2200	1.0710	0.594	1.026	.	.	.
66	06/26/85	27	Cogswell	cl	N	30	35	35	1.50	22.0	6.4610	0.4400	0.486	0.662	0.336	1.50	22.0
67	06/26/85	530	Cogswell	cl	W	30	35	35	1.50	22.0	5.9440	0.3460	0.486	0.662	0.318	1.56	22.0
68	06/27/85	28	Sonita	sl	SN	62	20	18	1.78	12.0	0.1610	1.3720	0.683	1.511	.	.	.
69	06/27/85	531	Sonita	sl	W	62	20	18	1.78	12.0	4.1900	0.4064	0.486	0.662	0.892	1.70	9.0
70	06/28/85	29	Grabe	l	XN	30	47	23	.	.	.	.	.	.	.	.	.
71	06/28/85	532	Grabe	l	XW	30	47	23	.	.	.	.	.	.	.	.	.
72	07/02/85	30	Comoro	sl	N	60	30	10	1.62	8.0	1.4020	0.7270	0.622	1.151	4.229	1.54	9.0
73	07/02/85	533	Comoro	sl	SW	60	30	10	1.62	8.0	0.8680	1.0090	0.635	1.219	.	.	.
74	07/03/85	31	Tubac	scl	N	50	27	23	1.43	10.0	3.8840	0.4080	0.566	0.914	1.075	1.66	13.0
75	07/03/85	534	Tubac	scl	W	50	27	23	1.43	10.0	2.0930	0.8486	0.551	0.858	2.145	1.67	11.0
76	07/08/85	32	Cogswell	cl	SN	30	35	35	1.52	18.0	0.3580	0.1852	0.675	1.455	.	.	.

OBS	DATE	FILE	SOIL	TEXTURE	ROW	SAND	SILT	CLAY	BDB	MB	K	A	WPR	WP	T	BD	M
77	07/11/85	535	Rositas	s	N	96	0	4	1.59	5.4	6.9910	0.8097	0.587	0.994	0.502	1.47	4.4
78	07/11/85	33	Rositas	s	W	96	0	4	1.59	5.4	4.8870	0.7120	0.621	1.145	0.755	1.61	5.6
79	07/12/85	34	Supersti	s	N	90	4	6	1.56	11.0	3.8670	0.8356	0.613	1.109	1.041	1.56	9.8
80	07/12/85	536	Supersti	s	W	90	4	6	1.56	11.0	3.4180	0.7652	0.576	0.952	1.228	1.60	10.3
81	07/16/85	35	Gilman	sil	N	28	54	18	1.47	14.3	3.4100	0.2965	0.717	1.777	1.713	1.42	16.2
82	07/16/85	595	Gilman	sil	W	28	54	18	1.47	14.3	3.3800	0.2310	0.645	1.271	2.073	1.44	14.1
83	07/17/85	36	Indio	sil	SN	40	53	7	1.44	12.8	3.4670	0.9755	0.642	1.255	.	.	.
84	07/17/85	537	Indio	sil	SW	40	53	7	1.44	12.8	8.3950	0.6380	0.699	1.626	.	.	.
85	07/18/85	37	Holtvill	sil	N	40	40	20	1.60	13.6	2.1000	0.1284	0.753	2.139	151.163	1.48	13.6
86	07/18/85	538	Holtvill	sil	W	40	40	20	1.60	13.6	1.8910	0.3077	0.695	1.599	11.414	1.70	14.1
87	07/19/85	38	Indio(sa	sil	N	40	53	7	1.45	12.3	5.6750	0.3550	0.685	1.526	0.373	1.34	12.1
88	07/19/85	539	Indio(sa	sil	SW	40	53	7	1.45	12.3	1.6460	0.1960	0.851	4.006	.	.	.
89	08/08/85	39	Mohave	scl	N	57	16	27	1.62	11.3	4.5870	0.5058	0.675	1.456	0.763	1.70	12.1
90	08/08/85	540	Mohave	scl	W	57	16	27	1.62	11.3	4.6100	0.3581	0.588	1.000	0.673	1.75	14.6
91	08/09/85	40	Gila	l	SN	32	47	21	1.40	11.0	12.3740	0.8793	0.495	0.685	.	.	.
92	08/09/85	541	Gila	l	W	32	47	21	1.40	11.0	3.4580	0.3730	0.325	0.335	1.478	1.50	11.8
93	08/12/85	41	Gila	sil	SN	28	52	20	1.40	9.6	1.6252	0.5890	0.705	1.672	.	.	.
94	08/12/85	542	Gila	sil	W	28	52	20	1.40	9.6	5.1400	0.2223	0.643	1.263	0.324	1.54	12.1
95	08/13/85	42	Vekol	c	SN	28	30	42	1.70	17.9	1.0420	0.2420	0.549	0.854	.	.	.
96	08/13/85	543	Vekol	c	SW	28	30	42	1.70	17.9	2.2100	0.4222	0.607	1.079	.	.	.
97	08/15/85	596	Casa_Gra	cl	W	53	26	21	1.76	8.7	2.4990	0.3552	6.670	1.401	3.760	1.66	9.4
98	08/19/85	43	Casa_Gra	cl	SN	53	26	21	1.76	8.7	1.8630	0.1909	0.666	1.398	.	.	.
99	08/22/85	44	Gilman	l	SN	37	41	22	1.60	15.0	1.2380	0.4417	0.571	0.933	.	.	.
100	08/22/85	544	Gilman	l	W	37	41	22	1.60	15.0	1.6730	0.7260	0.679	1.482	3.332	1.50	.
101	08/27/85	45	Gadsden	c	SN	27.0	31.0	42.0	1.48	25.0	0.047	3.0850	0.735	1.937	.	.	.
102	08/27/85	545	Gadsden	c	W	27.0	31.0	42.0	1.48	25.0	3.425	0.2890	0.655	1.331	1.711	1.590	22.7
103	08/28/85	46	Sacso	l	SN	38.0	37.0	25.0	1.63	17.6	0.001	7.9530	0.630	1.191	.	.	.
104	08/29/85	47	Casa_Gra	fsl	N	69.0	19.0	12.0	1.60	9.6	1.967	0.3524	0.644	1.268	7.494	1.620	10.6
105	08/29/85	546	Casa_Gra	fsl	XW	69.0	19.0	12.0	1.60	9.6	3.092	0.1280	0.542	0.827	.	.	.
106	09/03/85	547	Marana	sicl	?W	33.0	40.0	27.0	1.50	9.0	0.474	0.8527	0.725	1.848	.	.	.
107	09/03/85	48	Marana	sicl	N	33.0	40.0	27.0	1.50	9.0	2.430	0.1206	0.651	1.307	62.346	1.200	12.0
108	09/25/85	49	Tubac	scl	N	50.0	27.0	23.0	1.53	15.0	7.330	0.4283	0.553	0.865	0.243	1.490	16.3
109	09/25/85	548	Tubac	scl	W	50.0	27.0	23.0	1.53	15.0	4.396	0.3796	0.512	0.735	0.780	1.390	17.6
110	09/26/85	50	Sonita	sl	N	62.0	20.0	18.0	1.75	14.5	1.467	0.4860	0.561	0.893	7.877	1.740	10.8
111	09/26/85	549	Sonita	sl	SW	62.0	20.0	18.0	1.75	14.5	3.042	0.5615	0.655	1.326	.	.	.
112	10/02/85	51	Comoro	sl	XN	65.0	25.0	10.0	1.71	12.0	0.662	0.3690	0.710	1.710	.	.	.
113	10/02/85	550	Comoro	sl	XW	65.0	25.0	10.0	1.71	12.0	0.458	0.6310	0.708	1.696	.	.	.
114	10/04/85	52	Grabe	l	SN	30.0	47.0	23.0	1.65	12.5	2.933	0.8371	0.658	1.344	.	.	.
115	10/04/85	551	Grabe	l	SW	30.0	47.0	23.0	1.65	12.5	4.775	0.7909	0.743	2.019	.	.	.

OBS	DATE	FILE	SOIL	TEXTURE	ROW	SAND	SILT	CLAY	BDB	MB	K	A	WPR	WP	T	BD	M
116	11/05/85	53	Cogswell	l	SN	30.0	35.0	35.0	1.70	.	4.644	0.9271	0.746	2.056	.	.	.
117	05/02/86	54	Holtvill	sic	N	6.8	43.8	49.4	1.83	.	9.622	0.5040	0.695	1.593	0.175	1.630	16.8
118	05/02/86	552	Holtvill	sic	W	6.8	43.8	49.4	1.83	.	4.888	0.5950	0.667	1.469	0.714	1.610	18.4
119	05/05/86	55	Gadsden	c	N	8.1	37.0	54.9	.	.	8.114	0.4320	0.608	1.087	0.195	1.530	21.8
120	05/05/86	553	Gadsden	c	W	8.1	37.0	54.9	.	.	5.349	0.5030	0.659	1.352	0.561	1.530	20.8
121	05/08/86	56	Rositas	ls	N	87.0	5.6	7.4	1.60	.	3.717	0.8360	0.710	1.716	1.092	1.670	7.5
122	05/08/86	554	Rositas	ls	W	87.0	5.6	7.4	1.60	.	4.038	0.7390	0.724	1.837	0.987	1.720	8.6
123	05/09/86	57	Supersti	sl	N	75.8	13.8	10.4	1.74	.	5.155	0.4680	0.670	1.422	0.582	1.650	7.2
124	05/09/86	555	Supersti	sl	W	75.8	13.8	10.4	1.74	.	5.527	0.5750	0.644	1.266	0.570	1.720	7.4
125	05/13/86	58	Laveen	sl	N	60.0	22.0	18.0	1.73	10.8	5.668	0.6520	0.649	1.292	0.586	1.640	9.3
126	05/13/86	556	Laveen	sl	W	60.0	22.0	18.0	1.73	10.8	4.472	0.6090	0.721	1.805	0.833	1.750	10.8
127	05/15/86	59	Laveen	sl	N	54.0	30.0	16.0	1.87	9.2	2.714	0.5170	0.694	1.589	2.117	1.790	9.2
128	05/15/86	557	Laveen	sl	W	54.0	30.0	16.0	1.87	9.2	3.885	0.5160	0.620	1.142	1.058	1.900	9.8
129	05/21/86	60	Tucson	l	N	50.0	30.0	20.0	1.77	6.9	4.027	0.3730	0.670	1.423	0.982	1.810	6.9
130	05/21/86	558	Tucson	l	W	50.0	30.0	20.0	1.77	6.9	3.948	0.5110	0.640	1.242	1.026	1.720	6.9
131	05/27/86	61	Glenbar	scl	N	10.0	57.0	33.0	1.63	.	3.693	0.3420	0.621	1.148	1.263	1.330	12.8
132	05/27/86	559	Glenbar	scl	W	10.0	57.0	33.0	1.63	.	2.675	0.3650	0.764	2.268	3.011	1.640	16.3
133	05/28/86	62	Valencia	sl	N	54.0	30.0	16.0	1.70	9.1	3.485	0.6170	0.742	2.017	1.250	1.750	11.6
134	05/28/86	560	Valencia	sl	W	54.0	30.0	16.0	1.70	9.1	2.288	0.4430	0.730	1.895	3.529	1.630	8.9
135	05/29/86	63	Mohall	cl	N	44.0	28.0	28.0	1.69	4.4	5.117	0.5010	0.650	1.301	0.612	1.560	8.3
136	05/29/86	561	Mohall	cl	W	44.0	28.0	28.0	1.69	4.4	3.204	0.3060	0.594	1.025	2.065	1.800	6.0
137	05/30/86	64	Mohall	scl	N	52.0	27.0	21.0	1.80	8.3	5.028	0.6050	0.582	0.973	0.685	1.780	8.9
138	05/30/86	562	Mohall	scl	W	52.0	27.0	21.0	1.80	8.3	2.951	0.4100	0.540	0.822	2.100	1.900	9.1
139	06/09/86	65	Gila	l	N	49.3	33.5	17.2	1.42	12.1	4.890	0.2383	0.557	0.880	0.430	1.420	15.2
140	06/09/86	563	Gila	l	W	49.3	33.5	17.2	1.42	12.1	3.507	0.3450	0.637	1.228	1.464	1.650	12.3
141	06/10/86	66	Tubac	sl	N	65.1	18.6	16.3	1.76	13.4	2.426	0.4430	0.587	0.996	3.092	1.680	12.1
142	06/10/86	564	Tubac	sl	W	65.1	18.6	16.3	1.76	13.4	4 .000	0.4140	0.596	1.031	1.000	1.980	11.3
143	06/16/86	67	Supersti	sl	N	75.8	13.8	10.4	1.76	.	6 .551	0.4230	0.636	1.224	0.312	1.690	5.4
144	06/16/86	565	Supersti	sl	W	75.8	13.8	10.4	1.76	.	5 .673	0.3750	0.458	0.590	0.394	1.910	5.2
145	06/17/86	68	Rositas	ls	N	87.0	5.6	7.4	1.60	.	5 .188	0.4900	0.589	1.002	0.588	1.320	7.8
146	06/17/86	566	Rositas	ls	W	87.0	5.6	7.4	1.60	.	5 .579	0.4990	0.605	1.073	0.513	1.590	9.1
147	06/18/86	69	Gadsden	c	N	8.0	37.0	55.0	1.86	.	1 .680	0.3330	0.639	1.241	13.533	1.780	10.5
148	06/18/86	567	Gadsden	c	W	8.0	37.0	55.0	1.86	.	1 .087	0.5190	0.695	1.594	12.309	1.570	10.5
149	06/19/86	70	Holtvill	sc	N	6.8	43.8	49.4	1.74	9.4	4 .795	0.2960	0.666	1.394	0.542	1.480	10.5
150	06/19/86	568	Holtvill	sc	W	6.8	43.8	49.4	1.74	9.4	2 .451	0.4040	0.671	1.429	3.361	1.783	8.9
151	06/24/86	71	Laveen	sl	SN	60.0	22.0	18.0	1.580	9.6	3. 405	0.8060	0.635	1.217	.	.	.
152	06/24/86	569	Laveen	sl	W	60.0	22.0	18.0	1.580	9.6	2. 537	0.3216	0.633	1.208	4.1197	1.54	13.4
153	06/25/86	72	Laveen	sl	N	54.0	30.0	16.0	1.650	6.9	4. 594	0.5110	0.699	1.629	0.7627	1.60	6.5
154	06/25/86	570	Laveen	sl	W	54.0	30.0	16.0	1.650	6.9	4. 682	0.5400	0.658	1.344	0.7471	1.79	7.7

OBS	DATE	FILE	SOIL	TEXTURE	ROW	SAND	SILT	CLAY	BDB	MB	K	A	WPR	WP	T	BD	M
155	07/02/86	73	Tucson	l	N	50.0	30.0	20.0	1.820	10.5	3.467	0.5375	0.699	1.624	1.3048	1.69	9.4
156	07/02/86	571	Tucson	l	W	50.0	30.0	20.0	1.820	10.5	5.843	0.3670	0.573	0.940	0.3561	1.52	7.6
157	07/14/86	74	Glenbar	sicl	N	10.0	57.0	33.0	1.510	16.5	3.530	0.1380	0.602	1.057	2.4738	1.65	19.7
158	07/14/86	597	Glenbar	sicl	W	10.0	57.0	33.0	1.510	16.5	2.147	0.2036	0.674	1.448	21.2446	1.67	18.6
159	07/16/86	75	Mohall	cl	N	44.0	28.0	28.0	1.498	7.8	3.290	0.5820	0.644	1.265	1.3990	1.65	10.2
160	07/16/86	572	Mohall	cl	W	44.0	28.0	28.0	1.498	7.8	1.648	0.4280	0.637	1.228	7.9391	1.54	20.4
161	07/17/86	76	Mohall	scl	N	52.0	27.0	21.0	1.660	6.9	3.691	0.6270	0.605	1.073	1.1368	1.74	5.8
162	07/17/86	573	Mohall	scl	W	52.0	27.0	21.0	1.660	6.9	2.392	0.4430	0.643	1.259	3.1920	1.62	9.1
163	07/24/86	77	Tubac	sl	N	65.1	18.6	16.3	1.430	15.2	1.183	0.6450	0.648	1.287	6.6111	1.66	13.8
164	07/24/86	574	Tubac	sl	W	65.1	18.6	16.3	1.430	15.2	2.695	0.5160	0.647	1.285	2.1496	1.62	14.3
165	07/25/86	78	Gila	l	XN	49.3	33.5	17.2	1.510	15.5	1.005	0.4250	0.634	1.215	.	.	.
166	07/25/86	575	Gila	l	XW	49.3	33.5	17.2	1.510	15.5	0.854	0.1610	0.678	1.472	.	.	.
167	07/31/86	79	Valencia	sl	N	54.0	30.0	16.0	1.450	8.9	2.089	0.8410	0.718	1.781	2.1650	1.75	10.0
168	07/31/86	576	Valencia	sl	XW	54.0	30.0	16.0	.	.	.	.	.	.	.	.	.
169	08/04/86	80	Gadsden	c	N	8.1	37.0	54.9	1.860	9.4	5.911	0.1910	0.690	1.557	0.1294	1.82	9.8
170	08/04/86	577	Gadsden	c	W	8.1	37.0	54.9	1.860	9.4	4.199	0.2740	0.720	1.799	0.8376	1.85	8.9
171	08/05/86	81	Holtvill	sc	XN	6.8	43.8	49.4	.	.	.	.	.	.	.	.	.
172	08/06/86	82	Rositas	ls	N	87.0	5.6	7.4	1.600	4.7	4.641	0.7290	0.692	1.575	0.8156	1.68	6.1
173	08/06/86	578	Rositas	ls	W	87.0	5.6	7.4	1.600	4.7	3.963	0.6600	0.662	1.368	1.0142	1.62	4.7
174	08/07/86	83	Supersti	sl	N	75.8	13.8	10.4	1.740	6.0	7.440	0.6874	0.660	1.357	0.4054	1.83	5.4
175	08/07/86	579	Supersti	sl	W	75.8	13.8	10.4	1.740	6.0	3.444	0.6960	0.682	1.502	1.2399	1.70	4.7
176	08/18/86	84	Tucson	l	N	50.0	30.0	20.0	1.670	11.7	5.969	0.4570	0.629	1.189	0.4165	1.63	11.8
177	08/18/86	580	Tucson	l	W	50.0	30.0	20.0	1.670	11.7	5.268	0.4080	0.616	1.123	0.5092	1.75	7.7
178	08/19/86	85	Laveen	sl	N	54.0	30.0	16.0	1.630	8.0	3.119	0.4100	0.696	1.606	1.8345	1.71	8.5
179	08/19/86	581	Laveen	sl	W	54.0	30.0	16.0	1.630	8.0	2.806	0.4210	0.617	1.130	2.3213	1.66	7.4
180	09/04/86	86	Mohall	cl	N	44.0	28.0	28.0	1.390	12.1	4.008	0.3240	0.634	1.211	0.9939	1.43	13.6
181	09/04/86	582	Mohall	cl	W	44.0	28.0	28.0	1.390	12.1	2.715	0.3860	0.661	1.367	2.7289	1.53	10.0
182	09/08/86	87	Mohall	scl	N	52.0	27.0	21.0	1.450	5.4	3.151	0.3830	0.726	1.856	1.8643	1.64	4.9
183	09/08/86	583	Mohall	scl	XW	52.0	27.0	21.0	1.450	5.4	4.079	0.2100	0.674	1.449	.	.	.
184	09/11/86	88	Glenbar	sicl	XN	10.0	57.0	33.0	1.590	21.0	3.255	0.0150	0.689	1.550	.	.	.
185	09/11/86	584	Glenbar	sicl	XW	10.0	57.0	33.0	1.590	21.0	1.983	0.0310	0.670	1.418	.	.	.
186	09/16/86	598	Valencia	sl	N	54.0	30.0	16.0	1.650	10.5	1.266	0.4940	0.702	1.647	10.2657	1.85	11.3
187	09/16/86	585	Valencia	sl	W	54.0	30.0	16.0	1.650	10.5	1.262	0.5800	0.716	1.764	7.3079	1.84	10.3
188	09/29/86	89	Gila	l	XN	49.3	33.5	17.2	1.610	6.6	2.256	0.3670	0.658	1.347	.	.	.
189	09/29/86	586	Gila	l	XW	49.3	33.5	17.2	1.610	6.6	2.698	0.2830	0.648	1.286	.	.	.
190	09/30/86	90	Tubac	sl	N	65.1	18.6	16.3	1.710	6.5	3.186	0.4880	0.680	1.487	1.5940	1.72	5.8
191	09/30/86	587	Tubac	sl	W	65.1	18.6	16.3	1.710	6.5	5.768	0.5890	0.710	1.710	0.5372	1.92	6.1

Legend

Texture	l	loam
	S	sand
	Si	silt
	C	clay
Row	N	non wheel
	W	wheel
	S	start up time uncertain
	X	major problems or data missing
	XXX	no data collected
Sand, Silt Clay		percentage of each
BDB		bulk density in bed
BD		bulk density in furrow
MB		moisture content in bed (%)
M		moisture content in furrow (%)
K		Kostiakov K, constant in power infiltration equation (in/hr^a)
A		Kostiakov A, exponent in power infiltration equation
WPR		ratio of actual to SCS wetted perimeters
WP		actual wetted perimeter (ft)
T		time to infiltrate 4 inches over wetted perimeter (hrs)

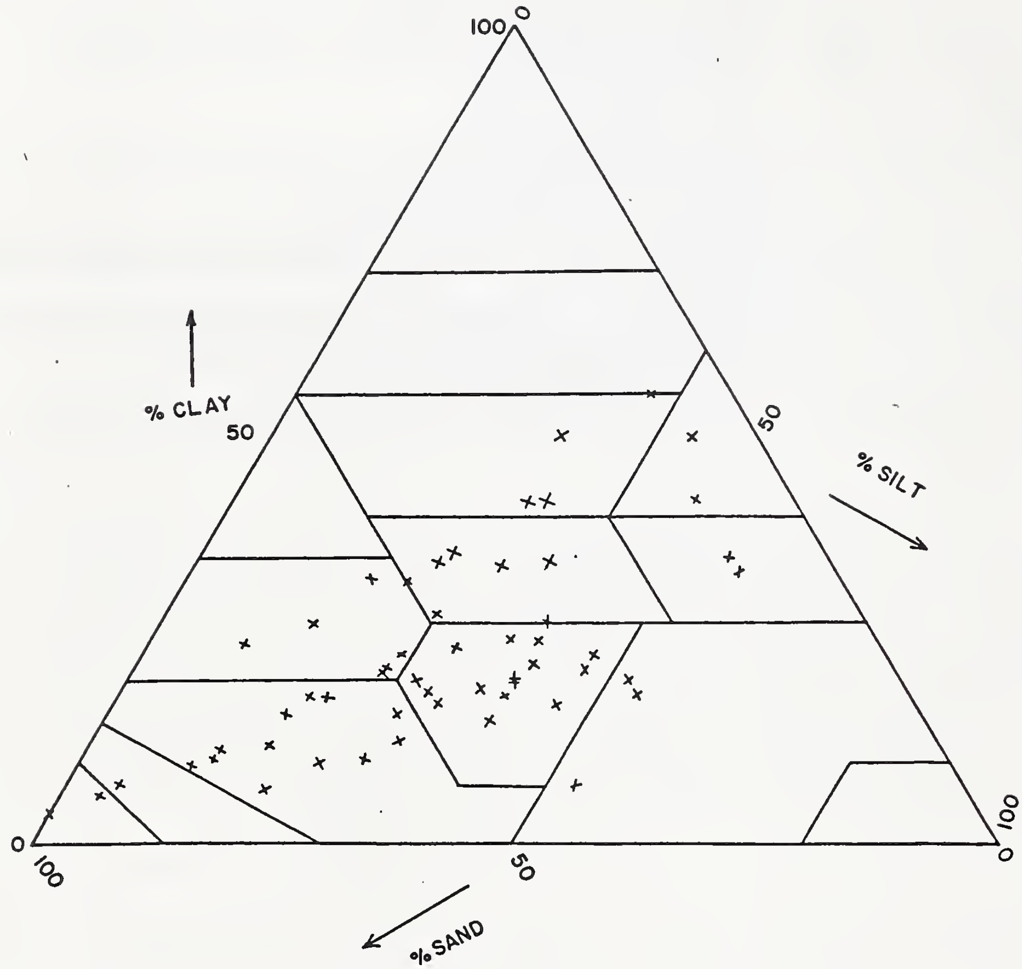


Figure 1. Texture of soils tested with flowing furrow infiltrometer in Arizona.

TITLE: Irrigation Water Delivery Performance Evaluation

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001-00D

INTRODUCTION

Overall project objectives tend to be long term and seasonal in nature, including such things as: augmenting crop production, economic improvement of area, betterment of general population, rural development, sustainable agriculture, minimizing the impact of irrigated agriculture on the environment, etc.. Day to day management of an irrigation water delivery system requires some measures of performance that can be evaluated quickly and easily. Those receiving water (and responsible for its delivery) are generally concerned with the reliability, adequacy, equity and consistency of the water deliveries. However, the things that we can measure include the flow rate, Q, duration, D, volume, V, and frequency, F, at any point within the system.

First, we must have some way of taking the raw measurements of conditions and translate these into expressions or performance measures which represent such things as reliability, adequacy, equity and consistency. Second, we must be able to determine the impact of these performance measures on the overall project objectives. This paper in concerned with the former problem. The later problem can only be addressed through detailed studies of existing conditions.

PERFORMANCE RATIOS

When measurements are taken at any point in the system, for example flow rate, there are three values that should be considered. These are the actual flow rate measured, Q_A, the flow rate that the operators intended to supply, Q_I, and the flow rate that is needed by the system (or farmers) downstream, Q_R. These three terms can be related as follows

$$Q_A/Q_R = Q_I/Q_R \;\; Q_A/Q_I \qquad (1)$$

If an adequate supply is provided, then Q_R/Q_A can be considered as an efficiency term. The ratio Q_I/Q_R is a measure of how well the intended flow rate matches the downstream requirements. For a rigid rotation system, it might be a measure of the plan for water delivery or the system design. It may also be a measure of the adequacy of the supply. (Q_I could be considered as the either the design discharge for the season or the discharge intended for the supply available, depending on what is being evaluated). For a flexible arranged delivery system, it measures the farmers' and water purveyor's abilities in ordering the correct amount of water. The ratio Q_A/Q_I is a measure of the delivery system's ability to supply water according to their plan. So the two ratios can be looked at as 1) how good is the plan and 2) how well is the plan being carried out. The performance of the operating staff is concerned with how well the plan is being carried out.

Suppose we are interested in evaluating the ability of a secondary canal (distributory) with fixed structures to distribute water to tertiary canals (water courses). In evaluating the ability of the structures to distribute water, we need to know the amount of water intended to be delivered at each outlet, Q_I, measure the actual rate of flow at each outlet, Q_A, and then compute the ratio of the two, $Q_{A/I} = Q_A/Q_I$. Over the secondary canal, there will be a range of values observed for this ratio, which can be represented by a frequency distribution, as shown in Figure 1. We can characterize the distribution by its mean value, $M_{QA/I}$, and standard deviation, $S_{QA/I}$, and need not measure every outlet. (More will be said about this later). If we assume that the values of these ratios are normally distributed, then we can relate the total actual flow of the secondary canal, Q_{S-A} with the intended flow into the secondary canal, Q_{S-I} (summation of intended flow to tertiary canals plus known losses) by

$$Q_{S-A} = Q_{S-I} \ (1 + z \ S_{QA/I}) \ \ldots\ldots \ (2)$$

As with the irrigation uniformity analysis methods, we can relate the value of z from the above equation with the percentage of outlets receiving the intended (adequate) amount, as shown in Table 1. This can be used in two ways. First if a sample of tertiary flows are measured from which $S_{QA/I}$ can be estimated and it is desired to have a certain percentage of outlets receive the desired amount (which sets z), then the needed secondary canal flow can be calculated. Second if in addition, Q_A for the secondary canal is measured, then the percentage of outlets not receiving sufficient water can be determined.

Theoretically when using a ratio of two normally distributed parameters, it is not appropriate to use a normal distribution for the ratio without first making a transformation. The problem is that the variance of the means is not constant over the whole range. However, if the coefficient of variation (and thus standard deviation since the mean equals unity) is less than 20% ($S_{QA/I} < 0.20$) then this error is insignificant. If this ratio is greater than 20% a serious problem in water distribution exists, even though the statistics are not quite appropriate. Another problem with this type of ratio is that if the denominator is equal to zero, the ratio blows up. In this situation, if $Q_I = 0$, we would simply exclude it from the analysis. If Q_A is zero, while $Q_I > 0$, then we would want to include it since it contributes to the non-uniformity of water application. The possibility of zero values causes problems even for a normal distribution, since the tails of the distribution extend to $\pm \infty$. Also, because the water received is typically no more than double that intended, the ratio Q_A/Q_I is much more behaved, ranging from roughly 0 to 2, whereas the inverse ratio would vary from 0.5 to ∞. If the ratios are distributed around unity and the standard deviation is less than 20%, then the values of $S_{QI/A}$ and $S_{QA/I}$ will be approximately the same. For example the probability that $Q_A/Q_I < 0.9$ is approximately the same as the probability that $Q_I/Q_A > 1.1$.

If we look at the difference between Q_I and Q_A relative to Q_I ($[Q_I - Q_A]/Q_I$), we get the same standard deviation as $S_{QA/I}$. Since it would not be as reasonable to determine this difference relative to Q_A, $S_{QA/I}$ should

be favored. In any case, these results need to be used with some caution. Assuming that the statistics are reasonable, we can use Equation 2 and Table 1 to determine the proportion of tertiary canals not receiving an adequate supply, A. In addition, we can also determine the average relative amount these tertiary canals are receiving, namely

$$U_{QA/I} = 1 - S_{QA/I}\, r \qquad (3)$$

Table 1. Statistical tables for Gaussian (Normal) Distribution.

Fraction of area adequately supplied, A	Relative distance from mean to intended supply z	Rel. distance from mean to ave. for undersupplied area t	Rel. distance from intend. to ave for undersupplied area r
0.50	0.000	0.798	0.798
0.55	0.126	0.879	0.753
0.60	0.253	0.966	0.713
0.65	0.385	1.058	0.673
0.70	0.524	1.159	0.635
0.75	0.674	1.271	0.597
0.80	0.842	1.399	0.557
0.85	1.037	1.554	0.517
0.90	1.282	1.754	0.471
0.95	1.645	2.061	0.416
0.955	1.695	2.106	0.411
0.960	1.751	2.154	0.403
0.965	1.811	2.207	0.396
0.970	1.881	2.267	0.386
0.975	1.960	2.336	0.376
0.980	2.054	2.419	0.365
0.985	2.170	2.522	0.352
0.990	2.327	2.661	0.334
0.995	2.575	2.883	0.308

where r is found from Table 1. The proportion of the required water supplied by the secondary canal (analogous to storage efficiency) can be found as

$$E_S = A + (1 - A)\, U_{QA/I} \qquad (4)$$

The conveyance efficiency of the secondary canal can also be found as

$$E_D = E_S / [1 + z\, S_{QA/I} + (\text{relative losses})] \qquad (5)$$

where the relative losses are such fixed losses as seepage and evaporation relative to the total canal flow. The $z\, S_{QA/I}$ and E_S terms represent regulation losses. End of canal spills, when considered regulation losses, would be added to the relative loss term.

So far, $S_{QA/I}$ gives a measure of spatial <u>equity</u> of operations and z (A and $U_{QA/I}$) gives us a measure of <u>adequacy</u> of operations. We can also look at these ratios temporally over the season. The temporal variation in the supply at any given location is a measure of the <u>reliability</u> of operations. To examine whether certain areas have more temporal variation than others, we can examine the covariance of the ratio over space and over time.

In open canals, we must also be concerned with the consistency of the flow rate in the canals. When water is introduced into a canal, a certain amount of time is required to fill the canal. In order to avoid over-topping when operating structures manually (and economically time wise), water is supplied to offtakes prior to the full flow rate arriving to that point. This is caused by the dispersion along the canal of a sudden flow rate change at the upstream end. Nearly all open canal system experience this problem, even though it may not be well recognized. The standard deviation of flow rates, S_Q, or the coefficient of variation of flow rates (S_Q/M_Q), C_Q, sampled periodically, can be used as a relative measure of equity to users (or fields) sharing the water over time downstream. Of course, this is only a relative measure since adjustments can be made to make the system more equitable. The time measurements of flow variation should be made on the same scale as the time distribution of water to users or fields.

The previous discussion have focussed on the performance of operations. Consideration should also be given to the performance of the plan or system design. The general equation for volume performance is

$$V_A/V_R = V_I/V_R \;\; V_A/V_I \quad \ldots\ldots\ldots\ldots \quad (6)$$

The value of V_I/V_R is much less than unity by intention. It is also intended that V_A be augmented (above V_I) through the use of tubewells. Thus achieving a good ratio of V_A/V_R. The seasonal variation in volume required can be compensated for through the use of the tubewell flows by varying pumping durations over the season. If such a supply does not exist, then one must be concerned with how the ratio V_I/V_R varies over the season. A fixed rotation schedule will have a very high $S_{VI/R}$ value temporally, since crop water requirements vary widely over the growing season. Such systems are thus susceptible to large shortages and/or poor efficiencies.

Example 1

Given: A secondary canal with 20 tertiary canals, which covers an area of 200 ha. The design flow is 500 l/s. The current intended flow is 400 l/s, or 80% of the design flow. The system is intended to distribute water proportionately according to area. The areas and actual flows to 8 tertiary canals are given below. The flow rate measured for the secondary canal was 405 l/s.

Find: 1) $S_{QA/I}$, z, A for 80% of the design flow
2) What is the average Q_A/Q_I for those receiving insufficient water?
3) What is the conveyance efficiency of the secondary canal?
4) What would Q for the secondary canal have to be for 90% of the tertiary canals to receive 80% of the design flow? 100%?

Tertiary canal Area, ha	Actual Flow Rate l/s	Intended Flow Rate l/s	Q_A/Q_I
8	17	16	1.063
9	21	18	1.167
12	22	24	0.917
10	19	20	0.950
11	20	22	0.909
9	19	18	1.056
10	21	20	1.050
11	20	22	0.909

1) The fourth column values have a standard deviation of $S_{QA/I} = 0.095$. The value of z can be found from Equation 2

$$z = \left[\frac{Q_A}{Q_I} - 1 \right] / S_{QA/z} = [(405/400)-1]/0.095 = 0.132$$

From Table 1, A = 0.552, or roughly 55% or 11 tertiary canals should receive the intended flow, 45% or 9 canals will not.

2) From Table 1, r = 0.751. From Equation 3,

$$U_{QA/I} = 1-S_{QA/t}\ (r)\ 1 - (0.095)\ 0.751 = 0.929,$$

or the nine canals not receiving an adequate supply receive an average of 93% of the intended supply

3) From Equation 4

$$E_S = A + (1-A)\ U_{QA/I}\quad 0.552 + 0.448\ 0.929 = 0.968$$

or 96.8% of the intended supply was delivered where it was intended. And by combining Equations 2 and 5

$$E_D = E_S(Q_{S-I}\ /Q_{S-A}\ )\ 0.968\ (400/405) = 0.956$$

or 95.6% of the water actually supplied was delivered where it was intended.

4) From Table 1 with A = 0.90, z = 1.282. From Equation 1

$$Q_{S-A} = 400\ (1 + 1.282\ 0.095) = 449 \text{ l/s for 80\% intended flow}$$
$$Q_{S-A} = 500\ (1 + 1.282\ 0.095) = 561 \text{ l/s for 100\% intended flow}$$

SELECTION OF PARAMETERS

In terms of project objectives, the ratio of actual/required is the most important. However, it is the product of the other two ratios. The A/R ratio could be evaluated separately. However, it might be misleading in that it would be difficult to identify the cause for the poor performance. It is particularly important to separate the performance of the operating personnel and physical system from the conceptual plan.

So far we have discussed 4 variables (Q,D,V,F), 3 ratios (A/R, A/I, I/R), 2 dimensions (space and time [seasonally plus short term for Q]), and three parameters (M, S, and z, plus interactions between space and time), for a total of about 96 parameters. A list of these parameters for the ratios A/I and I/R are given in Table 2. At this point we have no firm recommendations on which of these to use in evaluating different projects. The parameters to be chosen depend upon 1) what aspect of the system is being evaluated (operators, structures, design, plan, etc.), 2) site specific conditions, and 3) which of these parameters have the most impact on the project objectives.

Once the existing conditions are established, it is also necessary to determine what represents an acceptable value of that particular performance parameter. This must be chosen according to the project benefits and costs associated with meeting this performance level. Often times, there are unquantifiable factors which need to be considered as well. For example, improvements in delivery performance often allow farmers to learn about their farm system since many unknowns associated with water delivery have been removed. Once acceptable levels have been determined for various performance parameters, the operating staff have target values to shoot for. Some form of continuous monitoring is needed in order to determine whether target values are being met. These target values and monitoring program provide a focus for management of the water distribution system, since areas of low performance are easily identified.

SUMMARY

Measurement of the performance of irrigation water supply systems can be very difficult. While overall performance is related to seasonal results (e.g., yields, environmental quality, etc.), other measurements can be taken on a day to day basis to assist in management. These measurements include flow rates, volumes, and durations and the frequency of delivery. The idea is to compare actual values to the required values for each of these variables at each point in the system which is of interest. This ratio can be divided into two parts: the ratio of actual to intended flow is a measure of the performance of operations. The ratio of intended to required flow is a measure of performance of the scheduling plan or design.

Spatial and temporal statistics of these ratios can be used in a sampling scheme to determine measures of equity, adequacy and reliability of the water supply.

Table 2.--Irrigation Water Delivery Performance Evaluation Parameters

Flow Rate Ratio, Q_A/Q_I - performance of operations

$M_{QA/It}$ - mean value of the ratio of actual over intended flow rate at a given site over time (season) - a measure of efficiency at a location

$S_{QA/It}$ - standard deviation of the ratio of actual over intended flow rate at a given site over time (season) - a measure of reliability

$z_{QA/It}$ - number of standard deviations between unity and mean value of actual to intended flow rate ratio over time - a measure of temporal adequacy at a site

$M_{QA/Ix}$ - mean value of the ratio of actual over intended flow rate at a given time over space (season) - a measure of efficiency at a given time

$S_{QA/Ix}$ - standard deviation of the ratio of actual over intended flow rate at a given time over space - a measure of equity

$z_{QA/Ix}$ - number of standard deviations between unity and mean value of actual to intended flow rate ratio over distance - a measure of spatial adequacy at a given time

$S_{QA/Ixt}^2$ - covariance between spatial and temporal effects on Q_A/Q_I - measure of interaction between reliability and equity of flow rates

$S_{QA/Id}$ - standard deviation of the ratio of actual over intended flow rate for time intervals during an individual delivery - a measure of consistency?? - note $S_{QA/Id} = M_{QA/I}\ C_{QA}$ if Q_I is constant, where C_{QA} is the coefficient of variation of measured flow rates (mean over standard deviation)

$z_{QA/Id}$ - number of standard deviations between unity and mean value of actual to intended flow rate ratio during a delivery - measure of adequacy of delivery and uniformity of distribution among fields

Flow Rate Ratio, Q_I/Q_R - performance of plan or design

$M_{QI/Rt}$ - mean value of the ratio of intended over required flow rate at a given site over time (season) - a measure of efficiency at a location

$S_{QI/Rt}$ - standard deviation of the ratio of intended over required flow rate at a given site over time (season) - a measure of appropriateness??

$z_{QI/Rt}$ - number of standard deviations between unity and mean value of intended to required flow rate ratio over time - a measure of temporal adequacy at a site

$M_{QI/Rx}$ - mean value of the ratio of intended over required flow rate at a given time over space (season) - a measure of efficiency at a given time

$S_{QI/Rx}$ - standard deviation of the ratio of intended over required flow rate at a given time over space - a measure of equity

$z_{QI/Rx}$ - number of standard deviations between unity and mean value of intended to required flow rate ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{QI/Rxt}^2$ - covariance between spatial and temporal effects on Q_I/Q_R - measure of interaction between <u>appropriateness</u> and <u>equity</u> of flow rates

<u>Volume Ratio, V_A/V_I</u> - performance of operations

$M_{VA/It}$ - mean value of the ratio of actual over intended Volume at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{VA/It}$ - standard deviation of the ratio of actual over intended Volume at a given site over time (season) - a measure of <u>reliability</u>

$z_{VA/It}$ - number of standard deviations between unity and mean value of actual to intended Volume ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{VA/Ix}$ - mean value of the ratio of actual over intended Volume at a given time over space (season) - a measure of <u>efficiency</u> at a given time

$S_{VA/Ix}$ - standard deviation of the ratio of actual over intended Volume at a given time over space - a measure of <u>equity</u>

$z_{VA/Ix}$ - number of standard deviations between unity and mean value of actual to intended Volume ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{VA/Ixt}^2$ - covariance between spatial and temporal effects on V_A/V_I - measure of interaction between <u>reliability</u> and <u>equity</u> of Volumes

$S_{VA/Id}$ - standard deviation of the ratio of actual over intended Volume delivered to individual fields areas during an individual delivery - a measure of <u>consistency</u>?? - note $S_{VA/Id} = M_{VA/I}\ C_{VA}$ if V_I is constant, where C_{VA} is the coefficient of variation of measured Volumes (mean over standard deviation) - (this is not independent of farmer decisions)

$z_{VA/Id}$ - number of standard deviations between unity and mean value of actual to intended Volume ratio during a delivery - measure of <u>adequacy</u> of delivery and uniformity of distribution among fields (this is not independent of farmer decisions)

<u>Volume Ratio, V_I/V_R</u> - performance of plan or design

$M_{VI/Rt}$ - mean value of the ratio of intended over required Volume at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{VI/Rt}$ - standard deviation of the ratio of intended over required Volume at a given site over time (season) - a measure of <u>appropriateness</u>??

$z_{VI/Rt}$ - number of standard deviations between unity and mean value of intended to required Volume ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{VI/Rx}$ - mean value of the ratio of intended over required Volume at a given time over space (season) - a measure of <u>efficiency</u> at a given time

$S_{VI/Rx}$ - standard deviation of the ratio of intended over required Volume at a given time over space - a measure of <u>equity</u>

$z_{VI/Rx}$ - number of standard deviations between unity and mean value of intended to required Volume ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{VI/Rxt}^2$ - covariance between spatial and temporal effects on V_I/V_R - measure of interaction between <u>appropriateness</u> and <u>equity</u> of volumes

<u>Duration Ratio, D_A/D_I</u> - performance of operations

$M_{DA/It}$ - mean value of the ratio of actual over intended Duration at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{DA/It}$ - standard deviation of the ratio of actual over intended Duration at a given site over time (season) - a measure of <u>reliability</u>

$z_{DA/It}$ - number of standard deviations between unity and mean value of actual to intended Duration ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{DA/Ix}$ - mean value of the ratio of actual over intended Duration at a given time over space (season) - a measure of <u>efficiency</u> at a given time (time during season)

$S_{DA/Ix}$ - standard deviation of the ratio of actual over intended Duration at a given time over space - a measure of <u>equity</u>

$z_{DA/Ix}$ - number of standard deviations between unity and mean value of actual to intended Duration ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{DA/Ixt}^2$ - covariance between spatial and temporal effects on D_A/D_I - measure of interaction between <u>reliability</u> and <u>equity</u> of Durations

$S_{DA/Id}$ - standard deviation of the ratio of actual over intended Duration for individual fields areas during an individual delivery - a measure of <u>consistency</u>?? - note $S_{DA/Id} = M_{DA/I}\ C_{DA}$ if D_I is constant, where C_{DA} is the coefficient of variation of measured Durations (mean over standard deviation) - (this is not independent of farmer decisions)

$z_{DA/Id}$ - number of standard deviations between unity and mean value of actual to intended Duration ratio during a delivery - measure of <u>adequacy</u> of delivery and uniformity of distribution among fields (this is not independent of farmer decisions)

<u>Duration Ratio, V_I/V_R</u> - performance of plan or design

$M_{DI/Rt}$ - mean value of the ratio of intended over required Duration at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{DI/Rt}$ - standard deviation of the ratio of intended over required Duration at a given site over time (season) - a measure of <u>appropriateness</u>??

$z_{DI/Rt}$ - number of standard deviations between unity and mean value of intended to required Duration ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{DI/Rx}$ - mean value of the ratio of intended over required Duration at a given time over space (season) - a measure of <u>efficiency</u> at a given time (time during season)

$S_{DI/Rx}$ - standard deviation of the ratio of intended over required Duration at a given time over space - a measure of <u>equity</u>

$z_{DI/Rx}$ - number of standard deviations between unity and mean value of intended to required Duration ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{DI/Rxt}{}^2$- covariance between spatial and temporal effects on D_I/D_R - measure of interaction between <u>appropriateness</u> and <u>equity</u> of durations

<u>Frequency Ratio, F_A/F_I</u> - performance of operations

$M_{FA/It}$ - mean value of the ratio of actual over intended Frequency at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{FA/It}$ - standard deviation of the ratio of actual over intended Frequency at a given site over time (season) - a measure of <u>reliability</u>

$z_{FA/It}$ - number of standard deviations between unity and mean value of actual to intended Frequency ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{FA/Ix}$ - mean value of the ratio of actual over intended Frequency at a given time over space (season) - a measure of <u>efficiency</u> at a given time (time during season)

$S_{FA/Ix}$ - standard deviation of the ratio of actual over intended Frequency at a given time over space - a measure of <u>equity</u>

$z_{FA/Ix}$ - number of standard deviations between unity and mean value of actual to intended Frequency ratio over distance - a measure of spatial <u>adequacy</u> at a given time

$S_{FA/Ixt}{}^2$- covariance between spatial and temporal effects on F_A/F_I - measure of interaction between <u>reliability</u> and <u>equity</u> of Frequencies

<u>Frequency Ratio, V_I/V_R</u> - performance of plan or design

$M_{FI/Rt}$ - mean value of the ratio of intended over required Frequency at a given site over time (season) - a measure of <u>efficiency</u> at a location

$S_{FI/Rt}$ - standard deviation of the ratio of intended over required Frequency at a given site over time (season) - a measure of <u>appropriateness</u>??

$z_{FI/Rt}$ - number of standard deviations between unity and mean value of intended to required Frequency ratio over time - a measure of temporal <u>adequacy</u> at a site

$M_{FI/Rx}$ - mean value of the ratio of intended over required Frequency at a given time over space (season) - a measure of <u>efficiency</u> at a given time (time during season)

$S_{FI/Rx}$ - standard deviation of the ratio of intended over required Frequency at a given time over space - a measure of <u>equity</u>

$z_{FI/Rx}$ - number of standard deviations between unity and mean value of intended to required Frequency ratio over distance - a measure of spatial adequacy at a given time

$S_{FI/Rxt}{}^2$- covariance between spatial and temporal effects on F_I/F_R - measure of interaction between appropriateness and equity of frequencies

(Note: for I/R ratios, V, Q and D can not be looked at independently. There has to be assumptions made about which is required to be some value(s).)

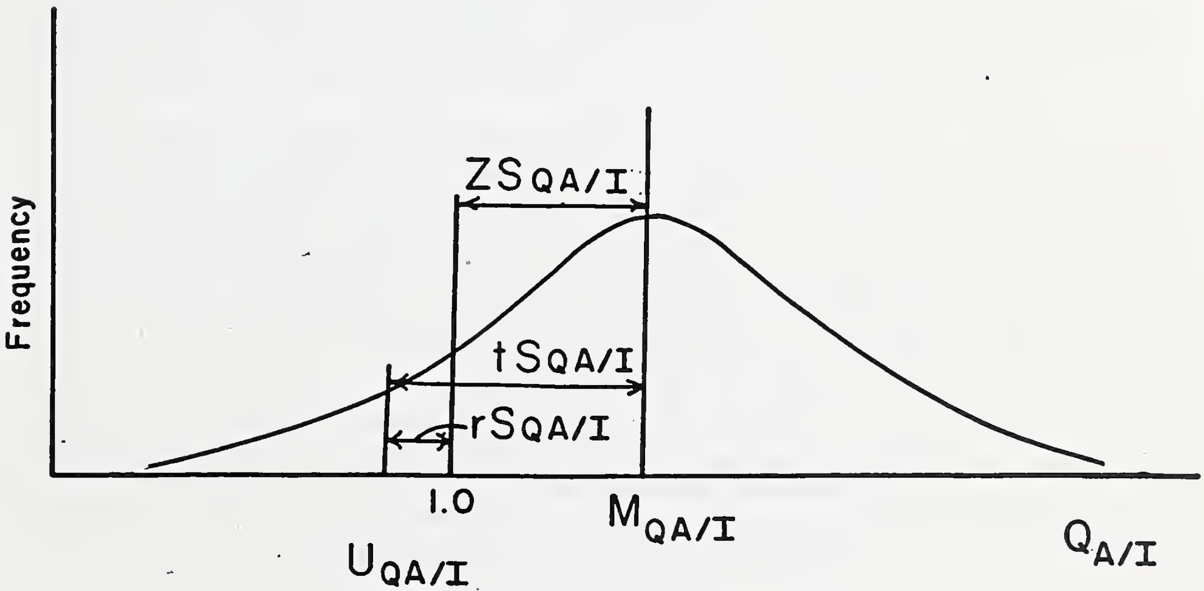


Figure 1. Frequency distribution of actual to intended flows.

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PERSONNEL: A. J. Clemmens, J. D. Palmer, W. Clyma

TITLE: Statistical Irrigation Uniformity Analysis Methods

SPC: 1.3.03.1.d CRIS WORK UNIT: 5344-13000-001-00D

INTRODUCTION

It has been well demonstrated that the uniformity of irrigation water application has an effect on crop yields (Letey, 1985, Hunsaker and Bucks, 1986 and Solomon, 1985). These results come from a combination of field studies and theoretical considerations. Extending these results to any particular field for determining irrigation schedules, for controlling the irrigation process, or for irrigation system design is particularly difficult due to the number of contributing factors which are difficult to evaluate. Actual field measurements of irrigation uniformity are both difficult and expensive to make. In addition, attainable uniformity has an impact on potential irrigation efficiency, and thus influences the amount of water needed to grow a particular crop at a particular yield. Frequently, "experience" is used to integrate all these considerations. Unfortunately, this usually results in less than optimal results.

All irrigation methods are inherently nonuniform in their application of water. The variability of the applied water can be expressed in terms of the standard deviation of water depth applied to different parts of a field (Till and Bos, 1985). The size of area over which applied depths are considered should be on the same scale as plant and root influence (Lety, 1985). Irrigation management suggests the use of a "target" depth of application. This target is typically the soil moisture deficit at the time of irrigation, or management allowed deficit (MAD), although for deficit irrigation or for the effective use of rainfall, a lower value may be used. Because of the nonuniformity of water application, it is often that some portion of the field does not receive this target amount of water, while most of the field receives more than the target amount. The following relation can be used to relate the mean or average depth applied (infiltrated), M_D to the target or required depth, R_D

$$M_D = R_D + S_D\, z \quad (+\text{ runoff}) \qquad (1)$$

where S_D is the standard deviation of applied (infiltrated and redistributed) depth values and z is a relative measure of how far M_D and R_D are apart. For this analysis, runoff is ignored. If the type of water distribution is known (e.g., normal or log-normal), then z can be related to the irrigation adequacy, A, or the percentage of field area which has received at least the target amount of water. In some cases, the depths are normally distributed, while in others they are not. Usually the distributions are close enough to a normal distribution that this distribution can be assumed. Table 1 gives the relation between the values of z and A, which can be found in standard statistical table as the area under a normal curve.

Use of Table 1 is fairly straight forward. Suppose the target depth, R_D, is 10 cm and the standard deviation of depths for the irrigation method, S_D, is 2 cm. (Methods for determining S_D will be discussed in more detail

in later sections). If we would like to adequately irrigation 80% of the field area, from Table 1 we find z = 0.842. Substituting these values into Equation 1 gives M_D = 10 + 2 (0.842) = 11.68 cm. We need additional information on how much water was infiltrated into the area receiving less than the target depth in order to determine such things as storage efficiency, application efficiency, etc. For a normal distribution, this information can be obtained from the other two columns in Table 1. The average depth infiltrated over the area receiving less than the target amount of water, U_D, can be found from

$$U_D = M_D - S_D\, t = R_D - S_D\, r \qquad (2)$$

where t is the relative distance (relative to S_D) between M_D and U_D and r is the relative distance between R_D and U_D. For our example, the average depth in the underirrigated area is U_D = 10 - 2 (0.557) = 8.89 cm. The storage efficiency is defined as the volume of water infiltrated and stored divided by the volume which could be infiltrated and stored. Here this is limited to the target amount, not to the soil moisture deficit. The storage efficiency thus defined is

$$E_S = [A\, R_D + (1-A)\, U_D]/R_D \qquad (3)$$

For our example, E_S = [0.80 10 + 0.20 8.89]/10 = 0.978. The application efficiency is defined as the useful amount infiltrated and stored (within target) divided by the amount applied, or

$$E_A = [A\, R_D + (1-A)\, U_D]/M_D \qquad (4)$$

For our example, E_A = [0.80 10 + 0.20 8.89]/11.68 = 0.837. Values for storage efficiency and application efficiency can be computed for different values of adequacy once the required depth and standard deviation are known. This assumes that the standard deviation for a particular irrigation method does not depend on the depth applied. For surface systems, this is a reasonable assumption within a range of typical application depths. Of significance is that S_D is primarily a function of the irrigation system (for surface systems it can be altered slightly by changing operations and conditions) and z is a function of management, namely what tradeoff am I willing to accept between area adequately irrigated and efficiency. For our example, we can express these trade offs by solving Equations 1 through 4 for different values of A, as shown in Table 2. Such a table can be constructed for any values of R_D and S_D.

For sprinkler and micro systems the standard deviation is not constant but varies directly with the depth applied. Thus for sprinkler and micro system, it is more convenient to work with the coefficient of variation, C_D which is the standard deviation divided by the mean. Dividing Equation 1 by M_D and rearranging gives

$$R_D/M_D = 1 - C_D\, z \qquad (5)$$

The amount received in the underirrigated area relative to the amount needed can also be found by dividing Equation 2 by R_D

$$U_D/R_D = 1 - (R_D/M_D)\, C_D\, r \quad (6)$$

The storage and application efficiencies can then be found as a function of A and the two ratios defined in Equations 5 and 6

$$E_S = A + (1-A)\, U_D/R_D \quad (7)$$

$$E_A = E_S\, R_D/M_D \quad (8)$$

If C_D and A are known, the remaining ratios can be directly computed (again assuming no runoff or direct losses). Thus a table of values for R_D/M_D, U_D/R_D, E_S and E_A can be constructed as a function of A for a particular C_D value, as shown in Table 2. For a normal distribution of infiltrated depths, the low quarter distribution uniformity (average of quarter area of the field receiving least amount of water divided by the average depth infiltrated) is

$$DU = 1 - 1.27\, C_D \quad (9)$$

From this and values generated as in Table 2, the merits of the irrigation can be determined from which to judge the mean depth to apply M_D. In this way, the impacts of irrigation uniformity can be quantified.

Returning to the surface irrigation conditions, where the standard deviation remains nearly constant, C_D varies with the depth applied and so is not known ahead of time. What is known are S_D and R_D. Define $G_D = S_D/R_D$. Then the ratios R_D/M_D and U_D/R_D can be found in terms of G_D

$$R_D/M_D = (1 + G_D\, z)^{-1} \quad (10)$$

$$U_D/R_D = 1 - G_D\, r \quad (11)$$

The equations for E_S, E_A and DU remain the same. A table similar to Table 2, but with G_D as a constant instead of C_D, can also be constructed.

It should be remembered that these relations derived include several assumptions. First that the distribution of depth values in normally distributed. In previous articles (Clemmens, 1986 and Clemmens, 1987) I have pointed out that this is not entirely correct. Hydraulic pressure distributions (trickle and sprinkler) and opportunity time distributions (surface) tend to be non-Gaussian. For pressure distributions on flat terrain, uniformities are actually better than would be predicted by this analysis. For level-basin opportunity time distributions, uniformities are actually worse. Fortunately, other factors which are more nearly random are often more significant, making actual depth distributions nearly normally distributed. Second, for sprinkler and trickle irrigation, we assume that C_D is constant. This appears to be a good assumption, except for conditions such as emitter clogging, wind drift, and surface runoff from excessive application rates. These extra losses would have to be added to the gross depth applied. For surface irrigation, we assume that S_D is constant. First, S_D can be altered by

changing the stream size and thus advance and recession relations. There is also a tradeoff between uniformity, in terms of S_D, and runoff amount. That is, S_D can be decreased by increasing stream size and thus runoff. The intent here is not to evaluate these interactions, but simply to look at the implications of changes in S_D and R_D and their impact on efficiency and uniformity.

Till and Bos (1985) point out that S_D (or C_D) is a function of the system, while z (or A) is a management decision. If the current application efficiency is too low, the only options to raise it are to improve the system uniformity (lower S_D) or to allow greater deficits (smaller A).

Table 1. Statistical tables for Gaussian (Normal) Distribution.

Fraction of area adequately irrigated, A	Relative distance from mean to target, z	Rel. distance from mean to ave. for underirrig. area, t	Rel. distance from target to ave for underirrig. area, r
0.50	0.000	0.798	0.798
0.55	0.126	0.879	0.753
0.60	0.253	0.966	0.713
0.65	0.385	1.058	0.673
0.70	0.524	1.159	0.635
0.75	0.674	1.271	0.597
0.80	0.842	1.399	0.557
0.85	1.037	1.554	0.517
0.90	1.282	1.754	0.471
0.95	1.645	2.061	0.416
0.955	1.695	2.106	0.411
0.960	1.751	2.154	0.403
0.965	1.811	2.207	0.396
0.970	1.881	2.267	0.386
0.975	1.960	2.336	0.376
0.980	2.054	2.419	0.365
0.985	2.170	2.522	0.352
0.990	2.327	2.661	0.334
0.995	2.575	2.883	0.308

Table 2. Efficiency values as a function of area adequately irrigated for $S_D/M_D = C_D = 0.10$.

Fraction of area adequately irrigated, A	Ratio of Net to Gross Amount Applied, R_D/M_D	Ratio of Net over underirr. Area to Required Depth U_D/R_D	Storage Efficiency E_S	Application Efficiency E_A
0.50	1.000	0.920	0.960	0.960
0.55	0.987	0.926	0.967	0.954
0.60	0.975	0.931	0.972	0.948
0.65	0.962	0.935	0.977	0.940
0.70	0.948	0.940	0.982	0.930
0.75	0.933	0.944	0.986	0.920
0.80	0.916	0.949	0.990	0.906
0.85	0.896	0.954	0.993	0.890
0.90	0.872	0.959	0.996	0.868
0.95	0.836	0.965	0.998	0.834
0.955	0.831	0.966	0.998	0.829
0.960	0.825	0.967	0.999	0.824
0.965	0.819	0.968	0.999	0.818
0.970	0.812	0.969	0.999	0.811
0.975	0.804	0.970	0.999	0.803
0.980	0.795	0.971	0.999	0.794
0.985	0.783	0.972	1.000	0.783
0.990	0.767	0.974	1.000	0.767
0.995	0.742	0.977	1.000	0.742

STATISTICAL ANALYSIS OF COMBINED UNIFORMITY EFFECTS

With each irrigation methods, there are many factors which cause irrigations to be non-uniform. With existing methods, it is very difficult to quantify the effects of each of these factors on the irrigation uniformity. The approach taken here is to determine the mean value and the standard deviation (or coefficient of variation) for variables describing each factor, and then to statistically combine these to estimate the uniformity of applied water. There are two justifications to this approach. First, it may be easier to measure or estimate the magnitude and variability of these parameters than to measure the actual distribution of water. Second, such a technique would allow one to analyze the impact of the variation in each parameter on the distribution of applied water and irrigation uniformity. This analysis could be very useful in design or for making recommendations following an evaluation.

Bralts, et al. (1981) were probably the first to combine the effects of two sources of irrigation non-uniformity through the use of statistical equations. The statistical techniques for this are given in (Mood, et. al. 1974). While Bralts et al.'s work was for trickle irrigation, some parallels exist when a power function (i.e., Kostiakov equation) is used to describe surface irrigation infiltration (Clemmens, 1986).

An equation for the variance of infiltrated depths (and thus coefficient of variation) can be developed in terms of the variances of the individual parameters provided that the equation parameters which are allowed to vary can be expressed as simple products and sums. Jaynes and Clemmens (1986) have presented the basic statistical equations for determining the variance of infiltrated depths from the variances of the components which contribute to depth. In that article, variance equations were developed for the Philip and Kostiakov infiltration equations. The same theory will be used here to develop variance equations for a different set of conditions.

The basic statistical equations for the mean and variance of the sum of two random variables is (D = B + C)

$$M_D = M_B + M_C \quad \ldots\ldots \quad (12)$$

$$S_D{}^2 = S_B{}^2 + S_C{}^2 + 2S_{BC}{}^2 \quad \ldots\ldots \quad (13)$$

where $S_{BC}{}^2$ is the covariance of B and C which equals $\Sigma\,(B_i-M_B)(C_i-M_C)/(n-1)$. If B and C are independent, then $S_{Bc} = 0$ and

$$C_D{}^2 = M_C{}^2\, S_B{}^2 + M_B{}^2\, S_C{}^2$$

If D = B C, then

$$M_D = M_B M_C + S_{BC}{}^2 \quad \ldots\ldots \quad (14)$$

$$S_D{}^2 = M_C{}^2 S_B{}^2 + M_B{}^2 S_C{}^2 + 2M_C M_B S_{BC}{}^2 + 2M_B S_{CCB}{}^3 + 2M_C S_{BBC}{}^3 + S_{BBCC}{}^4 - S_{BC}{}^2 S_{CB}{}^2 \quad \ldots\ldots \quad (15)$$

If $S_{BC} = 0$, then

$$C_D^2 = C_B^2 + C_C^2 + C_B^2 C_C^2 \quad (16)$$

Surface Irrigation: A number of different factors influence the uniformity of water application in surface irrigation systems, which makes estimates of uniformity prior to an irrigation event particularly difficult. The factors which significantly affect irrigation uniformity are:

1). variations in infiltration opportunity time caused by differences in advance and recession curves (Merriam, 1985 and Clemmens and Dedrick, 1981),

2). variations in soil infiltration properties (Vieira, et al, 1981 and Bautista and Wallender, 1985),

3). variations in the surface retention of water (Dedrick, 1983), and

4). variations in water applied to different areas of a field (e.g., different application times for different irrigation sets).

Typical surface irrigation evaluations based on opportunity time alone essentially only consider the first factor. Several other factors that will not be considered here are the effects of surge irrigation on infiltration rates and the effects of wetted perimeter on furrow infiltration.

In this analysis, only the final infiltrated depth at each location in the field is significant, and not the entire cumulative infiltration curve. Thus, a simplified form of infiltration equation will be used, namely

$$D = b + c\,T + r \quad (17)$$

where D is infiltrated depth, b is the intercept of the cumulative infiltration relation, c is the final infiltration rate, T is the infiltration opportunity time, and r is the depth of surface storage or retention. Equation 17 is equivalent to the Kostiakov branch infiltration function at long irrigation times with surface retention added (Clemmens, 1983). This relation is shown in Fig. 2. This equation is reasonable in cases where the soil reaches a near constant infiltration rate prior to the end of an irrigation.

Each of the parameters in Eq. 17 can be considered to have both random variations and deterministic trends. The combination of variance methods used here theoretically apply only to random variables. If several random variables and one deterministic trend are present, the combination of variance equations still hold (See Clemmens, 1987). However, when more than one deterministic trend is present, these trend must be handled in a different manner, as demonstrated by Clemmens (1988).

If only random variations in the retention parameter (r) and opportunity time trends (T) are included, the standard deviation of depths can be found from

$$S_D{}^2 = S_r{}^2 + M_c 2 S_T{}^2 \quad (18)$$

Equations for the more general case can be found in Clemmens (1988).

For basins, the variation in opportunity time (for average recession) is directly related to the advance relation. Advance time and distance can be expressed by a function of the form

$$x = g\, T^h \quad (19)$$

at x = L the field length, $T = T_t$, the advance time, and $L = g\, T_t^h$. The standard deviation of T, S_T, can be related to T_t according to the advance exponent h. Between h = 0.4 and 1.0, the ratio S_T/T_t goes from 0.29 up to 0.3 and back down to 0.29. Thus $S_T = 0.3\ T_t$ can be used for the variation in opportunity time caused by advance.

Variations in recession are assumed here to be attributed to surface retention of water, r, which could be associated with the degree of leveling precision. Since the trend in retention, G(x), is a variation in depth, it would not be appropriate as a recession curve in time. Trends in recession time associated with irrigation hydraulics are included in the parameter T(x). Dedrick (1983) found on level basins that the standard deviation of soil surface elevations were typically about 12 mm and 23 mm for laser and non-laser controlled land leveling when graded to a plane surface. Undulating surfaces would be expected to have greater variations in retention.

<u>Surface irrigation examples</u>: Given the following for a level basin, determine S_D, DU, A, U_D, E_S and E_A. Assuming S_D is constant, what would the application and storage efficiencies be if 20% of the area were under irrigated.

Average depth applied, M_D = 10 cm,
Required depth, R_D = 8 cm
Advance time, T_t = 0.5 hours,
final infiltration rate, c = 0.4 cm/hour,
standard deviation of surface elevation, S_r = 1.5 cm
Solution: $S_T = 0.3\ T_t = 0.15$ hours
From Equation 10, $S_D{}^2 = (1.5)^2 + (0.4\ 0.15)^2 = 2.254\ cm^2$, S_D = 1.50 cm.
From Equation 9, DU = 1 - 1.27(1.5/10) = 0.810, or 81.0%
From Equation 1, z = (10 - 8)/1.5 = 1.333
From Table 1, estimate A = 0.91, or 91% of field adequately irrigated, and r = 0.463
From Equation 2, U_D = 8 - 1.5 0.463 = 7.31, or 9% of field got an average of 7.31 cm instead of 8 cm.
From Equation 3, E_S = [0.91 8.0 + 0.09 7.31]/8 = 0.992, or 99.2%
From Equation 8, E_A = 0.992 8/10 = 0.794, or 79.4%
Now let A = 0.80, then z = 0.842, r = 0.557
M_D = 8 + 0.842 1.5 = 9.263 cm, U_D = 8 - 1.5 0.557 = 7.165 cm
DU = 1 - 1.27(1.5/9.263) = 0.794, or 79.4%
E_S = [0.80 8.0 + 0.20 7.165]/8 = 0.979, or 97.9%
E_A = 0.979 8.0/9.263 = 0.846, or 84.6%.

Thus the application efficiency was increased 5% for less than 1.5% change in storage efficiency. This is not a general rule, but depends on the relation between S_D and R_D.

Trickle Irrigation: Under trickle irrigation, the two main factors which influence irrigation uniformity are the manufacturer's coefficient of variation of the emitter and the line pressure at the emitter. Since each emitter flows for the same amount of time, the depth is directly related to discharge, where

$$D = Q\,T / A = (k\,H^x)\,T / A \qquad (20)$$

where Q is flow rate, T is application time, A is area covered, H is line pressure and k and x are empirical emitter discharge constant. The variation in depth is thus related to the variation in emitter discharge constant, C_E, and effective pressure (H^x), C_H. From Equation 15, since pressure and emitter properties are independent, we get

$$C_D^2 = C_E^2 + C_H^2 + C_E^2\,C_H^2 \qquad (21)$$

For n emitters per tree and an emitter variation of C_M,

$$C_E^2 = C_M^2 / n \qquad (22)$$

Sprinkler Irrigation: Under sprinkler irrigation (with fixed locations), the amount of water received at any location in the field is a function of the sprinkler pattern overlap and the discharge rate of the sprinkler head, the later of which is related to pressure. The depth at any location can be described by

$$D = P\,Q\,T / A = P\,(k\,H^x)\,T / A \qquad (23)$$

where P is a variable which describes the sprinkler pattern (under constant pressure). In this case, k does not vary. The form of the equation is identical to Equation 21, except that the pattern is frequently affected by the pressure. Starting with Equation 15 and ignoring higher order terms, the relation becomes

$$C_D^2 = C_P^2 + C_H^2 + 2S_{PH}^2/(M_P M_H) \qquad (24)$$

Thus the relative interaction between the effective hydraulic pressure, H, and the pattern, P, must be evaluated.

EXTENSION OF FIELD UNIFORMITY TO MULTIPLE FIELD UNITS

Irrigation rarely consists of a single border, basin or set of furrows, but generally consists of multiple irrigation sets for a given crop. Even if each field has the same moisture deficit, the depth applied to each field will vary because of changes in flow rate with time, errors in amount of time applied to each set, and unaccounted for differences in areas. Assuming for now that areas are equal, we can describe the volume per unit area (which is differentiated from depth which refers to a single border) as

$$V/a = M_{V/a} + (Q - M_Q)(T - M_T)/M_a \quad (25)$$

where V = volume, a = area, Q = flow rate, T = set time, and M stands for mean value of the subscripted variable. The variance of the volume per unit area is

$$\begin{aligned} S_{V/a}^2 &= S_D^2 + (M_T/M_a)^2 S_Q^2 + (M_Q/M_a)^2 S_T^2 + 2S_{QT}^2/M_a^2 \\ &= S_D^2 + S_F^2 \quad (26) \end{aligned}$$

As before, the mean value and required value can be related by

$$M_{V/a} = R_D + z\, S_{V/a} \quad (27)$$

where z is a measure of the field variability of water application. The average application over the deficit area can also be found as

$$U_{V/a} = R_D - S_{V/a}\, r \quad (28)$$

Example: In our previous example, S_D = 1.5 cm, M_D = 10 cm, R_D = 8 cm. Given now that M_T = 0.5 hrs, S_T = 0.05 hrs, and S_Q = 0, find the values for z, $U_{V/a}$, E_S and E_A.

We can find $M_Q/M_a = M_D/M_T$ = 10 cm/0.5 hrs = 20 cm/hr. Substituting into Equation 26

$$S_{V/a}^2 = 1.5^2 + (20.0\ 0.05)^2 = 3.25\ cm^2 \quad S_{V/a} = 1.80\ cm$$

From Equation 27

$$z = (10 - 8)/1.8 = 1.109$$

which gives A = 0.865 (as opposed to 0.91 without the time variation). From Equation 28, with r = 0.556 from Table 1,

$$U_{V/a} = 8 - 1.8\ (0.556) = 7.00\ cm$$

(as opposed to 7.31 cm). Solving Equations 7 and 8,

$$\begin{aligned} E_S &= [8.0\ (0.865) + 7.0\ (0.135)]/8.0 = 0.983 \\ E_A &= 0.983\ 8.0/10.0 = 0.787 \end{aligned}$$

which are only slightly changed from 0.992 and 0.794.

It may also be of interest to determine what percentage of fields receive some specified degree of adequacy. We can define R_F as equal to the mean depth applied to a field to give a desired degree of adequacy, which is the same as M_D. Then we can define

$$M_F = R_F + S_F\, z_F \quad (29)$$

We can further define the average depth received by those fields that did not receive the target adequacy as

$U_F = R_F - S_F\ r_F$ .... (30)

If we want to know what percentage of fields received enough water to get 80% adequacy (A=0.8) for our example, we first calculate R_F, which is the M_D required to give A=0.8 (z=0.842)

$$R_F = 8 + 1.5\ 0.842 = 9.263 \text{ cm}$$
$$M_F = 10 = 9.263 + 1.0\ z_F,\ z_F = 0.737$$

giving $A_F = 0.769$, or 76.9% of the fields received an adequacy of 80% or better. The corresponding r value from Table 1 is 0.596. The average depth over the remaining fields is (Equation 30)

$$U_F = 9.263 - 1.0\ 0.596 = 8.667 \text{ cm}$$

which corresponds to

$$z = (8.667 - 8)/1.5 = 0.445$$

and A = 0.671. Thus 76.9% percent of the fields received the 80% adequacy, while the remaining 23.1% of the fields received an average adequacy of only 67.1%.

SUMMARY

A method has been presented for using information on the uniformity of an irrigation system for expressing tradeoffs between total water applied and both area and related depth of under-irrigations. These relations can then be used as a basis for management decisions on how much water to apply. These concepts were also extended to application of water to multiple field units.

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<u>PERSONNEL</u>: A. J. Clemmens

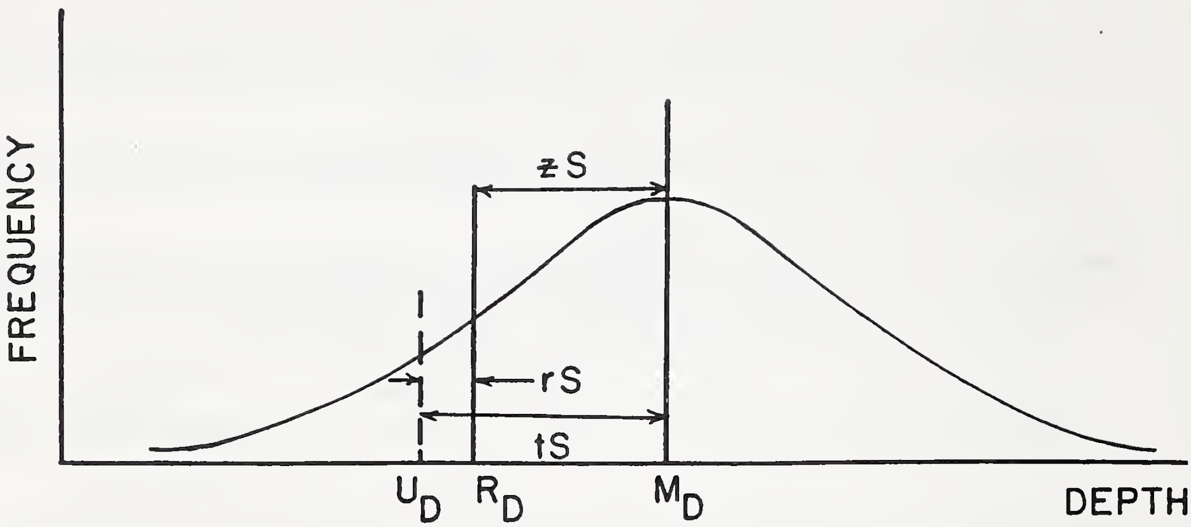

Figure 1. Frequency distribution of infiltrated depths.

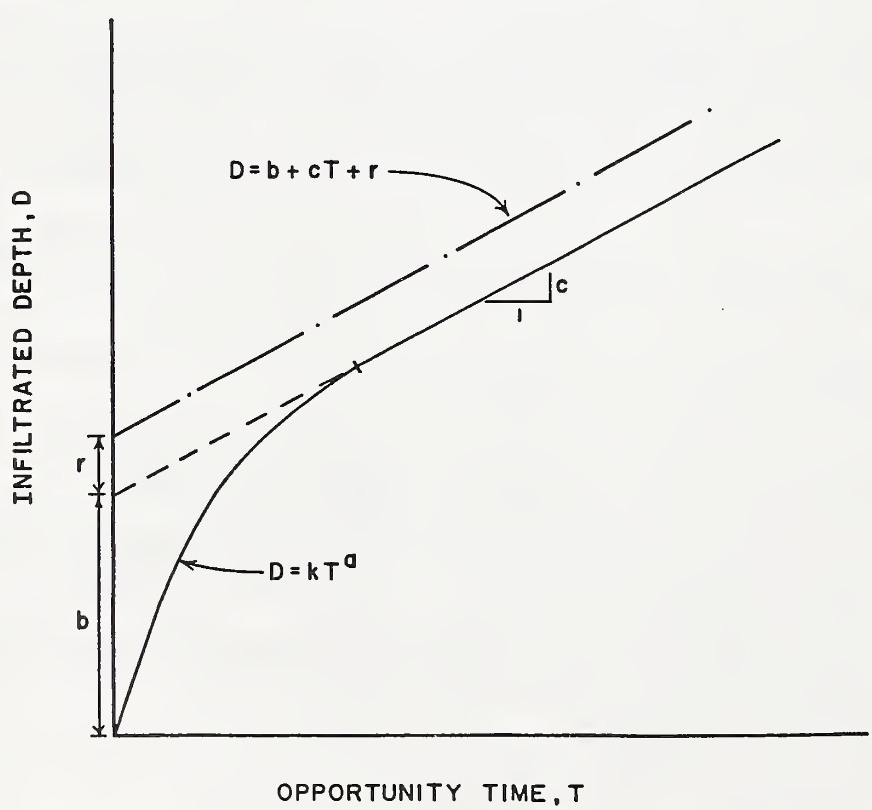

Figure 2. Kostiakov branch infiltration function with retention added.

TITLE: GUAYULE RUBBER QUANTITY AND QUALITY AS AFFECTED BY HARVESTING TECHNIQUES AND POST-HARVEST STORAGE

SPC: 2.3.04.1.p CRIS WORK UNIT: 5344-13220-001

INTRODUCTION

Rubber degradation in guayule has been noted in the early history of its culture (Curtis, 1947). According to Keller and Stephens (1982) the rubber is degraded by the resin constituent, most probably the unsaturated fatty acid linoleic acid. The oxidation of unsaturated fatty acids forms hydroperoxide which in turn initiates the degradation of the rubber molecule. Bhowmick, et al. (1985) noted that the degree of degradation based on molecular weight was higher the greater number of double bonds in the unsaturated fatty acids.

Adequate information is lacking as to how the harvested shrub should be handled prior to processing. We must presume that some degree of degradation would occur based on laboratory studies of rubber degradation and also with analogy to other field crops, but the extent of the change and how it would affect rubber extraction are unknown. Hammond and Polhamus (1965) reported that during the Emergency Rubber Project of the 1940's, the shrub was dug, windrowed, cured for 3 to 5 days to remove surface moisture, baled into 90.7 kg (200 lb) per bale, and shipped by trucks or rail to the mills. They indicated no plant deterioration of rubber during the transportation over long distances. The plant material was stored under cover for 10 to 12 days before processing. The limited study of Taylor and Chubb (1952) showed that fresh shrub gave the best rubber yield and highest molecular weight, followed by shrub that was defoliated and stored. An increase in recovered rubber occurred following storage between 3 to 6 weeks and then decrease with longer storage periods. The non-defoliated shrub with storage gave the lowest rubber yield and quality, but with a slight increase in resin yield.

Unpublished data of Dierig et al. (1988) at this laboratory indicated a decrease in rubber content and molecular weight after field storage of individual plants for six weeks in Central Arizona during the spring months. The degradation was minimal for the first two weeks, but became increasingly so after that. Also, they indicated that there was a varietal differences in the rate of degradation.

Wagner et al. (1986) obtained rubber that was soft and tacky from the Brawley, California shrub and attributed this possibly to the degradation of the latex when the shrub was stored for two weeks at summer ambient temperatures. In contrast, shrubs from other locations when stored under refrigeration for up to eight months gave rubber that was rigid and non-sticky. Black et al. (1986) also observed little change in rubber molecular weight when the shrubs were stored in the freezer for one year.

The present scenario is to harvest the shrub by clipping or rooting out the whole plant. From there the harvested material is stored in the field as whole plants and either chopped in the field or baled and then transported to the extraction facility for processing. Some field drying may be required to meet the needs of the processing facility.

Information is needed concerning the harvesting technology of guayule. Knowledge regarding the interrelation between harvesting method, baling or densification, transportation, and post-harvest storage conditions that would maximize rubber quantity and quality is important. The objectives of this project are to determine the effect of densification and storage on rubber quantity and quality and to determine whether there is any interactions of plant variety on rubber degradation.

PROCEDURE

The experiment involved determining the effect of field storage time on baled guayule shrub, comparison of different baled sizes, and plant varieties. Four varieties (N565-II, N576, 11605, and 12229) of mature plants in the 275m (900 ft) row were harvested with a specially designed and constructed digger made by Dr. Wayne Coates, cooperator in the experiment. The study was conducted at the University of Arizona Agricultural Field Station at Marana, Arizona.

Eight plants per replicate, with two replicates per row were sampled immediately after harvest for water, resin and rubber contents. Bales were made from the harvested shrubs at two, four, and eight day interval after harvest with the Gehl round baler. Two sizes of cylindrical bales, a large with dimension of 1.52 m wide x 1.83 m diameter weighing 907 kg (5 ft wide x 6 ft diameter, 2000 lb) and a small at 1.22 m wide x 1.22 m diameter and 450 kg (4 ft wide x 4 ft diameter, 1100 lb), were made. The bales were stored in the field. Plant samples were taken at weekly intervals after baling. The bales were cut into sections with a chain saw and at least eight plants were taken per section per replicate with two replicates per sampling for analysis. An initial grinding of the plant was made in the field with a chopper. The chopped material was sampled for water content determination to follow the drying behavior of the baled material. Another grinding was made at the laboratory the same day or the next with a garden-type shredder and the plant samples immediately frozen. A final grinding was made on a grinding mill (2 mm) prior to analysis using liquid nitrogen to help in the processing.

Gravimetric rubber and resin analyses were made following the method of Black et al. (1983). Water content of the shrub was determined at 50°C drying temperature.

RESULTS AND DISCUSSION

The rubber and resin contents for the 25 April 1988 harvest are listed in Tables 1 and 2. Varietal differences were present in respect to rubber content with lines N565-II and 11605 having significantly higher rubber than the N576 and 12229 lines. Resin content was significantly different among the lines with the order N565-II > 11605 > N576 > 12229.

The rubber content of the stored bales did not decrease with time over the 25 April to 27 May period. However, the rubber content in the first whole plant sample were significantly less than the stored plants (Table 2). This was present for all varieties and the possible reason for this result is the shedding of leaves during field drying and the baling process. Relatively little change in resin content was observed.

Rubber, resin, and water contents were not affected by baling two, four, and eight days after the plants were left in the field (Table 3). Temperature measurements within the bales showed no increase in bale temperature. The 06 June 1988 harvest also showed similar rubber and resin content behavior as the 25 April harvest in that the initial rubber contents were lower than the plant materials stored in the field. The resin content did not change with storage time. The rubber, resin and water contents were similar in the large and small bales (Table 4) and indicated that bale size did not affect storage quantity of the rubber or resin.

Plant samples are dried at 50° or 105°C following traditional procedures for characterizing water content in biological or physical materials, respectivcely, so that conversion from one method to another is needed in work where the two types of procedures are used. Results of drying at 50° and 105°C could be related by the following:

$$\theta_{50^\circ C} = -2.497 + 0.969\ \theta_{105^\circ C},\ r^2 = 0.999,$$

$$\theta_{105^\circ C} = 2.584 + 1.032\ \theta_{50^\circ C},\ r^2 = 0.999.$$

SUMMARY

The effect of storage on guayule rubber and resin contents was determined and included time of baling after harvest, bale size, and variety as the variables. The rubber and resin contents remained essentially constant over a one month field storage period. The time of baling after harvest and bale size had no significant effects on the rubber or resin content. However, the rubber content in the first sampling after harvest was consistently lower than the succeeding sampling dates. Varietal differences in rubber contents were observed following the order N564-II = 11605 > N565 = 12229 lines.

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PERSONNEL

F. S. Nakayama, B. A. Rasnick, J. M. Martinez; D. E. Powers, and W. Coates (cooperators).

Table 1. Guayule Varietal Relation to Resin and Rubber Contents.

Variety	Rubber Content %	Resin Content %
N565-II	8.01a*	8.71a
N576	6.40b	6.89c
11605	8.18a	7.65b
12229	6.42b	6.05d

* Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls' test. Lower case letters also indicate ranking.

Note: Harvested 25 April 1988.

Table 2. Effect of Storage Time on Guayule Rubber and Resin Contents.

Sampling Date	Rubber Content	Resin Content
25 April 88	6.55b*	7.14ab
29 April 88	7.18a	7.75a
13 May 88	7.62a	7.03b
20 May 88	7.30a	7.43ab
27 May 88	7.62a	7.27ab

* Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls' test. Lower case letters also indicate ranking.

Table 3. Effect of Storage Time and Time of Baling after Harvest on Guayule Rubber, Resin and Water Contents.

Baling time after harvest, day	Rubber content, %	Resin content, %	Water content, %
2	7.53a*	7.15a	16.0a
4	7.47a	7.25a	16.8a
8	7.38a	7.52a	17.2a
Sampling Date			
06 June 88	6.58b	7.11a	40.8a
14 June 88	7.93a	7.32a	11.2b
21 June 88	7.86a	7.60a	8.5c
05 July 88	7.48a	7.20a	6.2d

* Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls' test. Lower case letter also indicates ranking.

Table 4. Effect of Bale Size and Storage Time on Guayule Rubber, Resin and Water Contents.

Variety	Bale Size	Rubber Content, %	Resin Content, %	Water Content, %
N565-II	large	7.78a*	8.69b	9.65a
	small	7.78a	9.44a	9.13a
N576	large	6.51a	6.60a	10.1a
	small	7.21a	7.32a	10.1a
11605	large	8.70a	7.35a	10.0a
	small	9.03a	7.52a	10.4a
12229	large	5.79a	5.54a	10.4a
	small	5.92a	5.73a	10.0a

* Values followed by the same letters are not significantly different at the 5% level according to the Student-Newman-Keuls' test. Comparison tests were made within varieties.

TITLE: IRRIGATION AND ROW COVER EFFECTS ON DIRECT SEEDING OF GUAYULE

SPC: 2.3.04.1.p CRIS WORK UNIT: 5344-13220-001

INTRODUCTION

An experiment was conducted during the spring of 1988 at the University of Arizona Maricopa Agricultural Center, Marana, AZ, to determine the effects of irrigation levels, shade cloth, and a vermiculite seed covering on stand establishment of directly seeded guayule. Seeds of 11591 were planted on March 30 at a rate of 48 seeds per meter on raised beds that were spaced 1 m apart. Each plot comprised two 36-m rows. Six irrigation treatments were applied, all with biwall drip irrigation tubing. The wettest treatment (treatment #1) consisted of five irrigations per week for the first five weeks, and three irrigations per week for the second five weeks of the experiment. The driest irrigation treatment (#6) consisted of only an initial irrigation following planting; while the rest of the treatments consisted of intermediate irrigation levels. Three row cover treatments were applied: a check, which consisted of 10 mm of soil covering the seeds: vermiculite, applied several millimeters thick in a narrow band directly above the seed row; and a commercial shade cloth material that reduced midday solar radiation by 60%. Seedling counts and soil moisture content measurements were conducted weekly, while seedling water potential, plant height, and soil salinity were measured occasionally during the ten-week experiment.

RESULTS AND DISCUSSION

The three wettest irrigation treatments (#1-3) produced approximately twice the stand as the three driest treatments (#4-6) by two weeks after planting. From that point on, however, stands in treatments 1 and 2 declined rapidly to less than half of their maximum by week 10. Treatments 4 and 5 did not reach their maximum stands until week 4, but unlike the wetter treatments, their stands declined only slightly from their maximum by week 10, at which point their stand counts were higher than treatments 1 and 2. The driest treatment, #6, resulted in the lowest stand counts throughout the entire 10-week period. Stand count rankings of the six treatment at week 10, from highest to lowest, were 3, 5, 4, 2, 1, and 6, indicating that the intermediate irrigation levels resulted in the best stand establishment. Significant difference in stand establishment were also attributable to the different row covers, with the shade cloth producing the highest stand counts and check soil cover resulting in the lowest number of seedlings per meter or row.

PERSONNEL

S. G. Allen, D. A. Bucks, D. E. Powers, F. S. Nakayama, and W. L. Alexander

TITLE: CULTURAL MANAGEMENT OF LESQUERELLA

SPC: 1.3.03.1.d 80%
2.3.04.1.n 20%

CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

Cultural water management studies of lesquerella (Lesquerella fendleri) were started in the 1986-1987 season at the Maricopa Agricultural Center. The irrigation work carried out at that time was exploratory since no information was available on the water requirement of the crop. In fact the first planting was a failure because of poor plant establishment and new plantings had to be rescheduled two months later than originally intended. The experiment was repeated in 1988 and the experienced gained in the previous year was used in this set of study.

PROCEDURE

The 1987-1988 lesquerella crop was directed seeded on October 5, 1988, with a Stanhay belt seeder. Plant establishment was accomplished by sprinkler irrigation. As in the 1986-1987 experiment, a complete randomized block designed was used with four irrigation levels and four replications. A neutron access tube was placed in each plot to a depth of 180 cm and the water content monitored throughout the growing season, once before a flood irrigation and once after irrigation when it was possible to get into the field.

The four irrigation treatments consisted of the following:

Table 1. Irrigation Treatments of the Lesquerella Water Use Study for 1988.

Treatment Designation	Number Irrigations	Date of Irrigation (1988)
A	3	2/10, 3/8, 4/9
B	4	2/10, 2/29, 3/28, 4/28
C	5	2/10, 2/29, 3/22, 4/12, 5/3
D	6	2/10, 2/29, 3/15, 3/28, 4/12, 4/26

For the 1987 experiment, Treatments A, B, C and D had 1, 2, 4, and 5 irrigations and these were increased in 1988 to cover a wider range of water use patterns. Ammonium phosphate (16:20) was applied at the rate of 112 kg/ha (100 lb/ac). Plants were hand-harvested on 06 June 1988.

RESULTS AND DISCUSSION

The water use behavior of lesquerella for the four irrigation treatments are illustrated in Figures 1 through 4. The flowering pattern and plant size are also given in the figures. Flowering started at approximately the same date for all irrigation treatments and full flowering occurred in early April.

Seasonal water use, seed yield, and related plant parameters are presented in Table 2. For the water use of 400 to 626 mm, seed yields ranged from 660 to 1420 kg/ha, respectively. In 1987, seed yields were 140, 210, 440, and 570 kg/ha with 280, 340, 420, and 425 mm water use, respectively, at a December instead of the present October planting date. Significantly higher yields were attainable with higher water applications as shown in the 1988 experiment. Plant size, height and weight, and seed size were consistently higher with the higher water applications also. With earlier planting date in October, the harvest date could be moved ahead to the first week in June and possibly earlier compared to the July harvest when the planting was made in December.

SUMMARY

The second season of lesquerella water management study resulted in higher yields than the previous year. An October planting date permitted harvest in early June and such a cultural scheme could work well for double cropping. A better understanding of the water use pattern of the crop has been obtained. Acceptable yields are being obtained with existing bulk population and increased yields are anticipated with improved lines being developed.

PERSONNEL

F. S. Nakayama, W. L. Alexander, D. A. Dierig, E. R. Johnson, A. E. Thompson.

Table 2. Lesquerella Seed Yield and Other Related Plant Parameters to Various Irrigation Levels.

Treat-ment	Irrig. no.	Water Use, mm	Plant density, M/ha	Plant height, m	Plant weight, kg/ha	Seed weight, g/1000	Seed yield, kg/ha
A	3	400*	1.05a**	0.375a	5360a	0.485a	660a
B	4	550	1.16a	0.402a	7120b	0.488a	1060b
C	5	630	1.29a	0.435a	7860b	0.530a	1090b
D	6	630	1.44a	0.425a	9930c	0.514a	1420c

* Based on 150 cm depth probability level.

** Means with the same letter are not significantly different at the 0.01 probability level.

LIST OF FIGURES

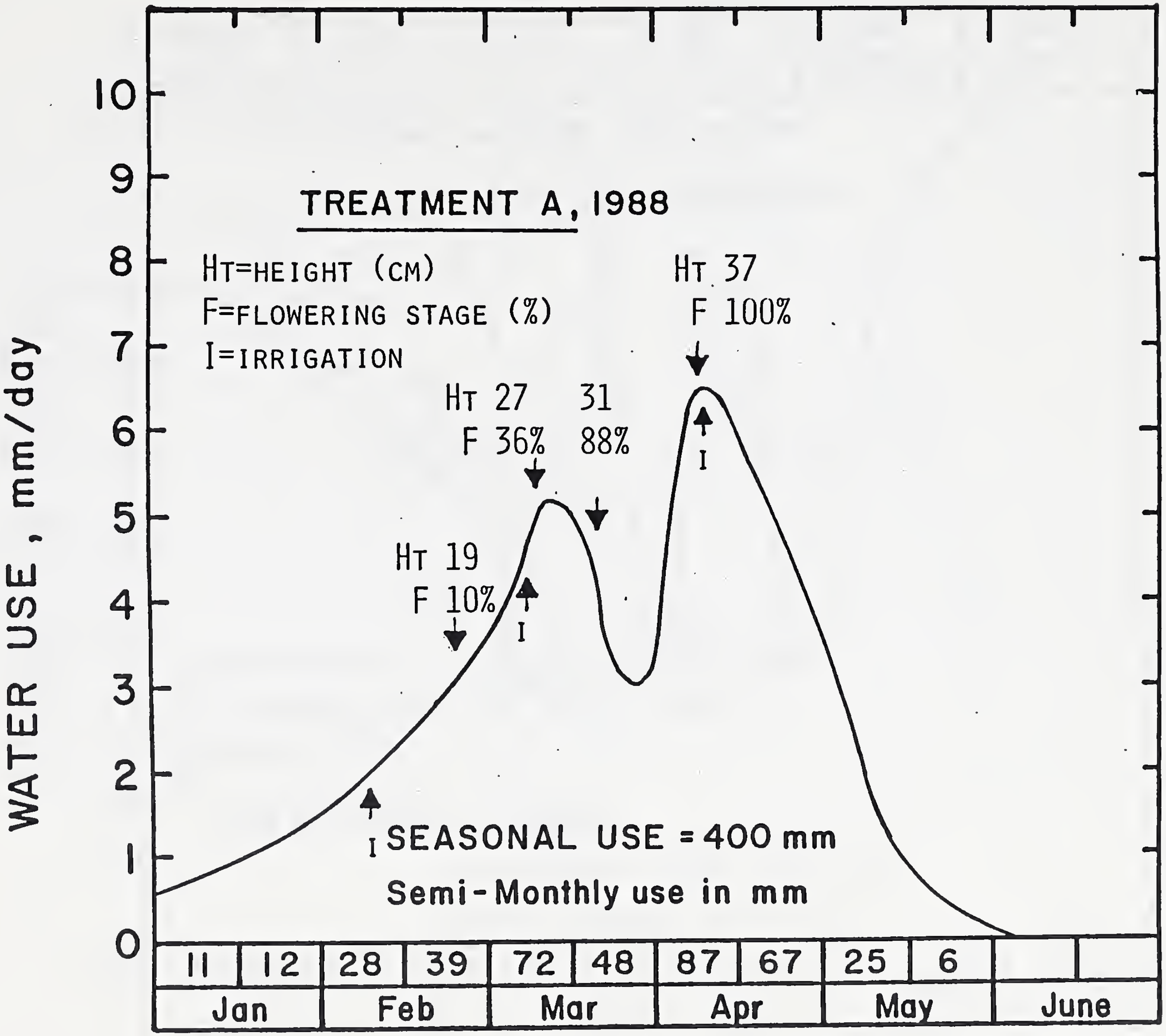
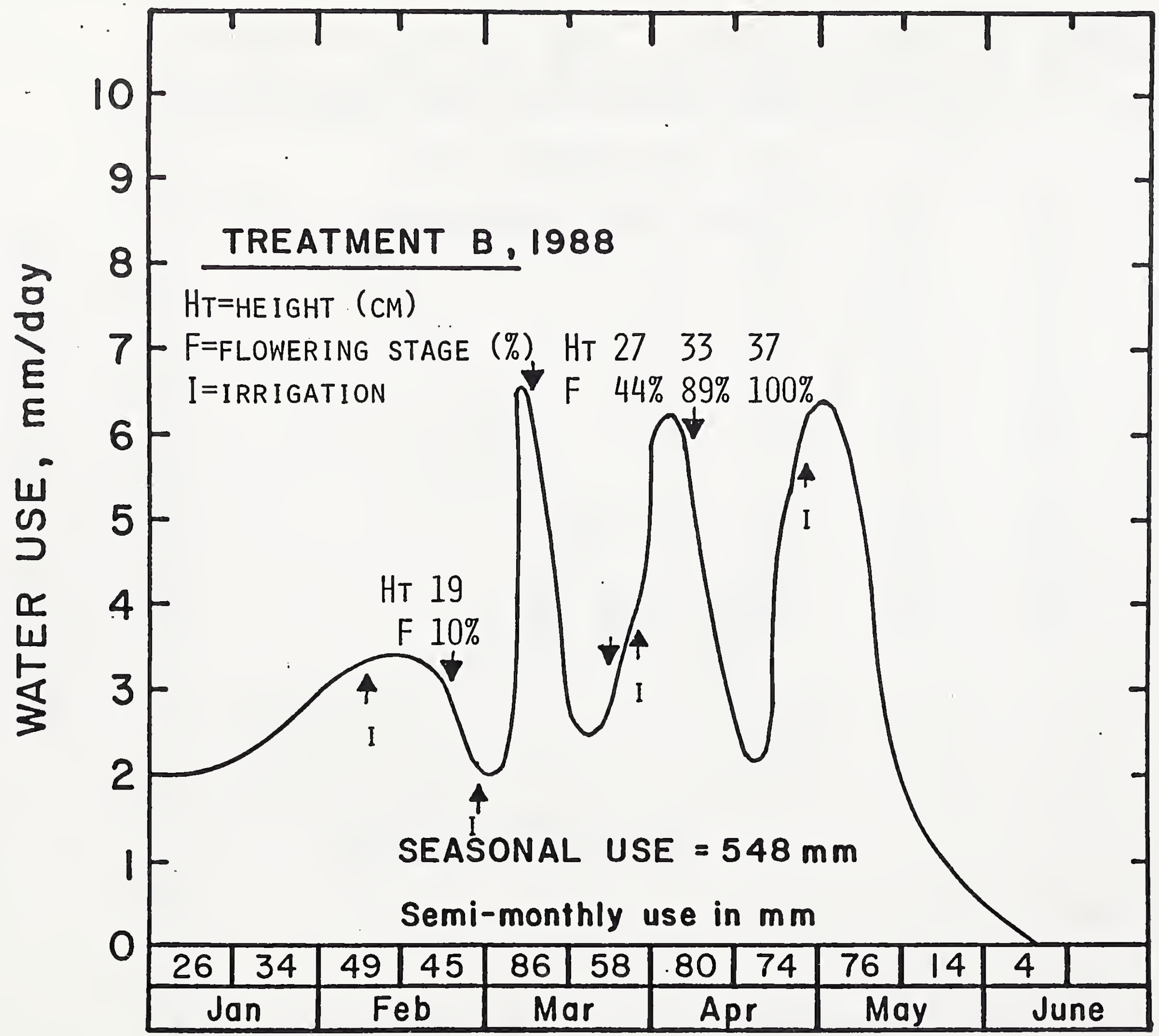


Figure 1. Seasonal water use for lesquerella, Treatment A (3 irrigations) at Maricopa, Arizona, 1987-1988.


TREATMENT B, 1988
HT=HEIGHT (CM)
F=FLOWERING STAGE (%)
I=IRRIGATION
HT 19
F 10%
HT 27 33 37
F 44% 89% 100%
I
SEASONAL USE = 548 mm
Semi-monthly use in mm
26 34 49 45 86 58 80 74 76 14 4
Jan Feb Mar Apr May June
WATER USE, mm/day
0 1 2 3 4 5 6 7 8 9 10

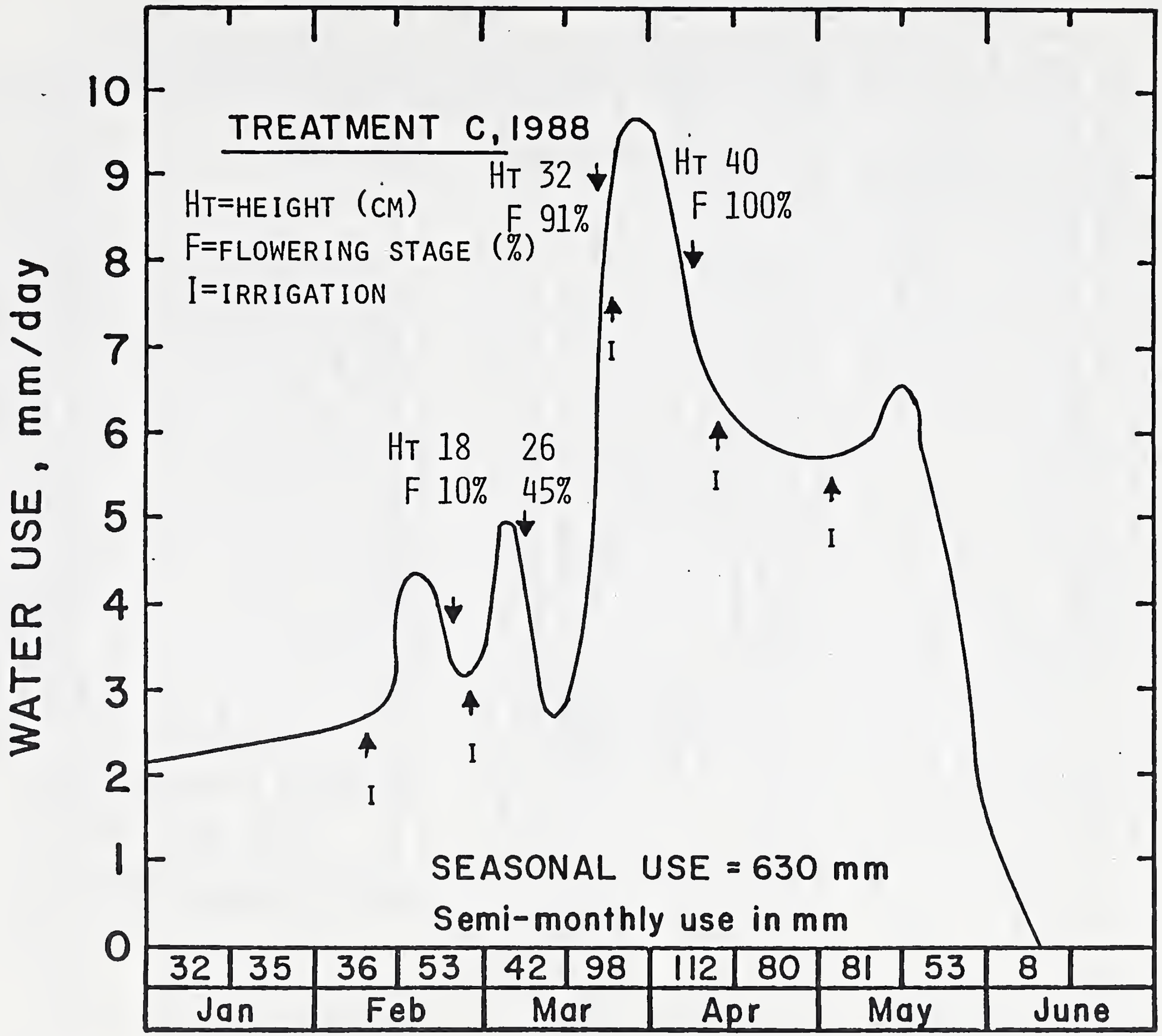
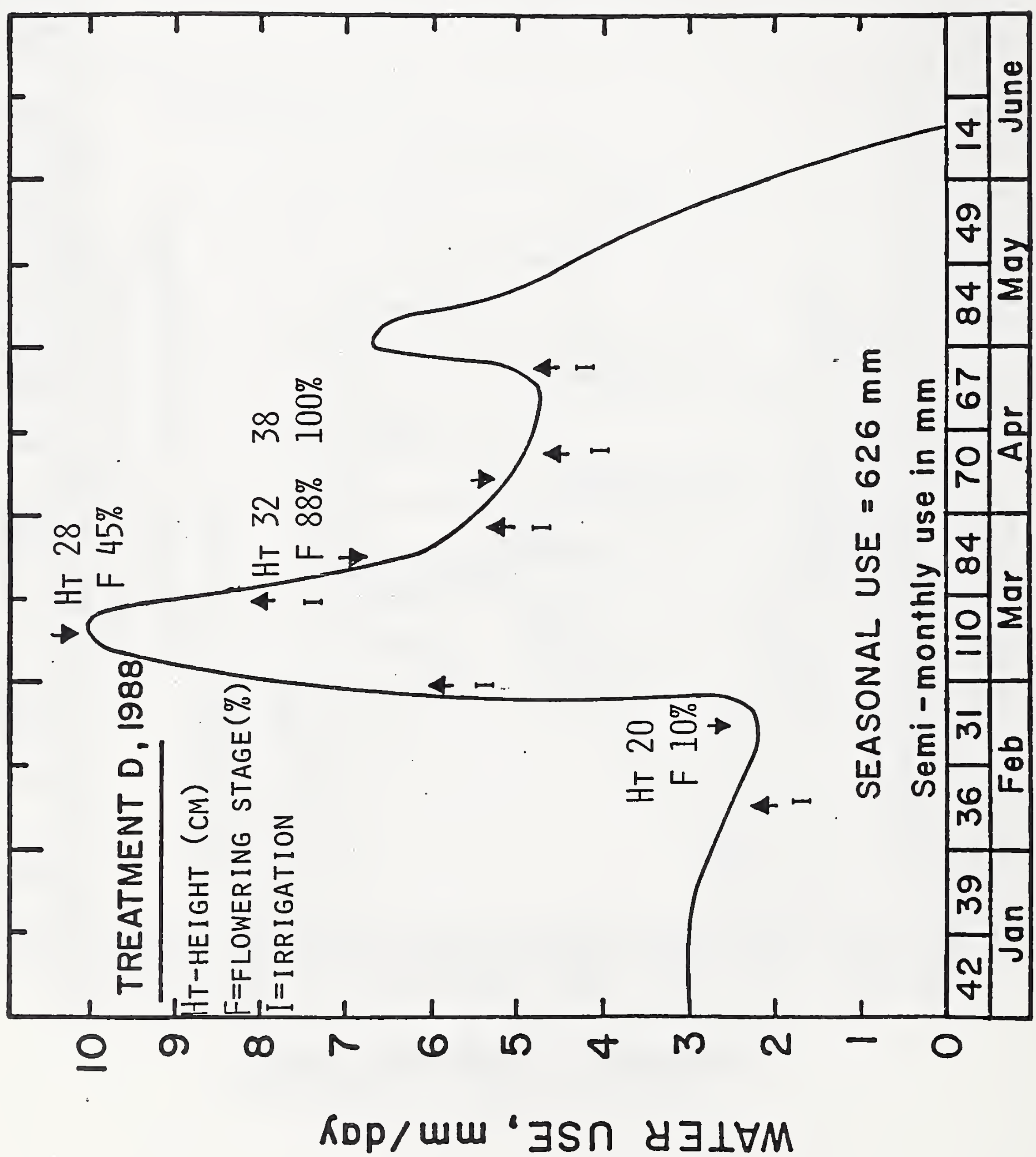


Figure 3. Seasonal water use for lesquerella, Treatment C (5 irrigations) at Maricopa, Arizona, 1987-1988.


TREATMENT D, 1988
HT-HEIGHT (CM)
F=FLOWERING STAGE(%)
I=IRRIGATION
HT 28
F 45%
HT 32 38
F 88% 100%
HT 20
F 10%
I
SEASONAL USE = 626 mm
Semi-monthly use in mm
42 39 36 31 110 84 70 67 84 49 14
Jan Feb Mar Apr May June
WATER USE, mm/day
0 1 2 3 4 5 6 7 8 9 10

TITLE: GERMPLASM IMPROVEMENT OF GUAYULE

SPC: 2.3.04.1.n 20%
1.3.03.1.d 80%

CRIS WORK UNIT: 5344-13230-001

A diverse population of guayule, Parthenium argentatum Gray, breeding material has been established at Maricopa Agriculture Center. The nursery was established in March 1988, consisting of 144 lines, totalling 7500 plants. Thirty eight more lines (2000 plants) were added in March, 1989. Most of these lines are single plant selections based on morphological characteristics such as regeneration capabilities, plant architecture, and high rubber and resin content. This germplasm will be used for continued selection work and breeding improvement. The majority of plants are facultative apomictic polyploids. However, some diploid, sexually reproducing plants have been identified in the population. These plants will be used later in a recurrent selection breeding program.

Replicated yield trials have been established over the past two years to evaluate selected lines. In 1988, 15 bulked lines were planted in a trial at Maricopa . These plants will be harvested in February, 1990 when they are two years old. In 1989, 23 lines were planted in a similar replicated trial. The same lines were also sent to Riverside CA for evaluation in another location. The first harvest will take place in February 1991.

In March 1989, 23 of the lines planted in the nursery the previous year were chosen for sampling based on their history of superior yields. Progeny of these same lines were used for the above mentioned 1989 yield trial. Branch samples were taken from ten plants of each line for rubber and resin analysis. The whole plant was also harvested by clipping at ground level and analyzed.

Rubber content varies throughout the branch of the plant. The younger branches have a higher rubber percentage than older branches, due to a higher bark to wood ratio. The purpose of harvesting branches and whole plants together is to devise an accurate sampling method that is representative of the whole plant and avoid destroying the plant in the process. This sampling technique would also allow easier handling of the samples since less plant material would be required. Normally plants are not at an optimum yield until two to three years of age. However, the performance of these lines after one year of growth is useful information that will be correlated with performance of two and three year old growth.

The effects of pollen sources on seed germination, seedling vigor and on the rate of apomixis is being examined. Pollination is required for viable seed production in facultative apomictic guayule, even though no characteristics of the male parent are transmitted to the progeny. This study compares germination and seedling vigor from the following treatments.

a) One guayule line in a single plot.
b) Two different guayule lines planted together in the same plot.
c) Two different guayule lines planted inside a shade screen cage to exclude pollinators.
d) One guayule line planted inside a shade screen cage containing bees to enhance pollination.
e) Two guayule lines planted inside a shade screen cage containing bees to enhance cross-pollination.
f) One guayule line and another Parthenium species, _P_. _incanum_, planted inside a shade screen cage containing bees to enhance interspecific cross-pollination.

When two different lines were planted inside a single plot, the two were uniformly interspersed. Each plot contains 12 plants and is replicated twice. Treatments will also be replicated over seasons. Transplants were field planted on March 27, 1989 at the Water Conservation Laboratory.

This study also hopes to examine the effects of cross pollination on the rate of facultative apomixis. The ratio of apomictic progeny to sexual progeny will be examined by isozyme analysis to determine the rate of apomixis.

At the study's conclusion, plants from each treatment will be harvested and analyzed for rubber content. This would determine whether or not a relationship exists between rubber content and pollination as previously reported in the literature.

PERSONNEL:

D. A. Dierig, A. E. Thompson, E. R. Johnson, D. H. Ronis, M. Perschbacker, B. A. Rasnick

TITLE: IMPROVING GUAYULE RUBBER YIELD WITH BIOREGULATORS

SPC: 2.3.04.1.p CRIS WORK UNIT: 5344-13230-001

INTRODUCTION

The yield of guayule (Parthenium argentatum) must be increased in order to make the crop economically feasible for production of natural rubber. Several methods are possible for achieving this goal. One is through the selection and breeding process, which by the nature of the perennial plant would be a long term approach. The other way is through the manipulation of the plant response to various types of chemical stimulants and/or suppressants which can enhance rubber production either by increasing rubber concentration or biomass or a combination of both.

Chemicals have been extensively used to improve crop yield or processibility--the most notable are the herbicides and defoliants (Best, 1983; Meister, 1985). Other more specialized chemicals which affect the plant directly are those used to improve fruit set or help in thinning shoots and fruit, control ripening, and storage of photosynthates (sugar). Applications are also numerous in the greenhouse industry to hasten or depress flowering, shoot growth, and to improve root initiation or transplant vigor (Nickell, 1983; Ory, 1984).

We have observed that the manual removal of flowers from the guayule plant increased rubber yield, both through the increase in rubber content and in plant biomass. Similar observations have been made by Willard and Ray (1986). Apparently, the photosynthate has been redirected toward plant growth and rubber synthesis from seed production by the removal of the flowers. Chemicals such as mefluidide has been used in the turf industry to suppress seed production. Others such as ethephon can promote fruit abscission.

Chemicals such as gibberellic acid have growth stimulating properties. Other chemicals can have both stimulating and suppressing properties depending upon the plant species and phenological time of application. The chemical DCPTA [2-(3,4-dichlorophenoxy)-triethylaminel] (Yokoyama et al., 1977), is the primary one used with guayule. Our work with this compound on a variety of guayule varieties has been unsuccessful so far for improving rubber yield. (Bucks et al., 1985; Annual Report 1987 - DCPTA effects on rubber and growth of guayule and several Parthenium species.)

Ideally, a bioregulator for use in guayule rubber production should do one or more of the following: (a) decrease flower production, (b) increase photosynthetic rate, (c) increase branching and stem size. The search for the ideal bioregulator is a challenge and would be based on experiences gained by others who used different compounds on various plant types. We will initially need a screening and developmental type approach and find the most promising compound or compounds and later select and focus in determining the optimal rate of application including the time, age,

season and variety of plant. Besides increasing yield, we look forward toward the applicability of chemicals to improve rubber quality, water-use efficiency, harvesting and post-harvest storage and handling.

EXPERIMENTAL DESIGN

A 3 x 3 lattice design with four replications was used on a 350 x 75 ft. plot. There were three chemical treatments at two concentration levels and a deflowering and the check for a total of 9 treatment combinations. The treatments were further divided into the "main plot" using chemicals available on the market place and "observation plots" using chemicals on the experiment stage of development with no guidelines on treatment levels available for commercial crops.

I. Plant variety
   A. C-250
   B. 11591

II. Treatment - main plot
   A. Non-bioregulator
      1. Check
      2. Manual deflowering - continuous
   B. Bioregulator
      1. Ethephon
      2. Gibberellic acid
      3. Daminozide

III. Treatment - observation plot
   A. Non-bioregulator
      1. Check
      2. Manual deflowering - Second year only
      3. Manual deflowering - Third year only

   B. Bioregulator
      1. Arsenal
      2. Pursuit
      3. Sceptor

PROCEDURE

Guayule seedlings were started in the greenhouse in January 1988 and repotted into Speedling trays. Field transplanting was made 07 April 1988 at the Maricopa Agriculture Center. Plants were established on standard beds at 1 meter (40-inch) row spacing with plant spacing of 61 cm (24-inch). Water was applied soon after transplanting and the plants maintained at optimal moisture level throughout the growing period.

Deflowering and chemical treatments were started 16 September 1988. The treatment levels low (L) and high (H) for the various chemicals were as follows:

1. Ethephon, L (2500 ppm), H (5,000 ppm)
2. Gibberellic acid, L (25 ppm), H (50 ppm)
3. Daminozide, L (0.25%), H (0.5%)
4. Arsenal, L (500 ppm), H (1,000 ppm, .06#/A)
5. Pursuit, L (500 ppm), H (1,000 ppm)
6. Sceptor, L (500 ppm), H (1,000 ppm)

The treatment rates for Arsenal, Pursuit, and Sceptor were one-tenth that recommended for weed control. The Pursuit and Sceptor solutions also had a 0.25% TWEEN-80 detergent included in the formulation to maximize leaf surface coverage. The solutions were sprayed on the plant to drenching.

RESULTS AND DISCUSSION

No visible difference in the treatment were observed in the deflowering or the ethephon, gibberellic acid and daminozide treatments. However, by approximately 3 weeks after spray treatment, no new flower formation was observed in the Arsenal, Pursuit and Sceptor treatments. By six weeks, however, sever dieback was present in the Arsenal and Pursuit treatments with essentially dead plants by mid-November eight weeks after treatment. The Sceptor treated plants had slight leaf damage, but were able to recover by December.

SUMMARY

A field experiment was set up to determine the effects of various bioregulators on guayule rubber yield. The fall treatment included six chemicals (ethephon, daminozide, gibberellic acid, Arsenal, Pursuit, and Sceptor) at two application levels.

Also included was a manual bud removal to control flowering. The Arsenal and Pursuit treatments, even at one-tenth the rate used for weed control, resulted in dead guayule plants. Reduction in flowering with some leaf damage was present with the Sceptor treatment. No visible plant changes were present with the ethephon, daminozide and gibberellic acid treatments. The experiments will continue for at least another year when the rubber yield data can be obtained.

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YOKOYAMA, H., HAYMAN, E. P., HSU, W. J., and POLING, S. M. 1977. Chemical bioregulation of rubber in guayule plant. Science 197:1076-1077.

PERSONNEL

F. S. Nakayama, S. G. Allen, and J. M. Martinez

TITLE: SOIL-PLANT-ATMOSPHERE INTERACTIONS AS RELATED TO WATER CONSERVATION AND CROP PRODUCTIVITY

SPC: 6.1.03.1.c (70%) CRIS WORK UNIT: 5344-13610-001-00D
1.1.02.1.b (30%)

INTRODUCTION

During 1988, the Soil, Plant, Atmosphere Systems Group published 18 papers and had 9 accepted for publication. The papers are summarized in the following paragraphs, along with a brief account of an intensive experiment conducted at the Maricopa Agricultural Center.

In previous annual reports the development of remote sensing techniques to evaluate evapotranspiration was described. Experiments conducted during 1988 concentrated on extending these techniques to use satellite data. Evapotranspiration rates calculated using surface temperatures obtained by the Landsat Thematic Mapper (TM) were compared with data calculated using aircraft data over several fields of cotton, alfalfa, and bare soil. The remote technique produced adequate values of evapotranspiration for uniform surfaces, but heterogeneous surfaces such as partial canopies still pose a problem in that the temperature of the evaporating surface cannot, as yet, be adequately specified.

Surface temperatures and reflectance factors of partial canopies such as row crops are difficult to evaluate. Plant temperatures may be 20 C lower than the surrounding soil. A model, requiring only information on row orientation and height and width of vegetative rows was developed. The model, using detailed ground-based surface temperature measurements, predicted the composite temperature obtained from aircraft data to within 1.5 C. Different soil backgrounds and different atmospheric conditions affect remotely sensed reflectance factor data obtained over partial canopies. How these factors affect various vegetation measures, and the magnitude of the resulting error if they are ignored, was demonstrated.

Measurements of surface reflectance factors in the field are usually made under conditions of total (direct and diffuse) irradiance, but reference reflectance panels are calibrated only for the direct irradiance. The magnitude of the error involved if only the direct irradiance reflectance factor is known, usually from laboratory calibration, was found to vary from -2% to +5%, depending on zenith angle, atmospheric conditions, and the particular reflectance panel used.

Using a radiative transfer model, a method was developed to obtain surface reflectance factor values from Landsat TM digital data. Differences between satellite-, aircraft- and ground-based surface reflectance factors over bare soil, at the same view and solar zenith angles, were within 0.014. A similar study was conducted for the High Resolution Visible (HRV) sensors aboard the SPOT satellite. Retrieving surface reflectance factors from HRV data is complicated by the fact that the view angle of the sensors can be changed, thus reflectance factor differences may be a

result of view angle rather than changes at the surface. A view angle correction was computed from ground-based measurements of radiance from bare soil at numerous view angles. When applied to several SPOT images, this view angle correction was sufficiently accurate to compensate for the different view angles.

The third major remote sensing experiment (MAC III) was conducted at the University of Arizona's Maricopa Agricultural Center during the period 10 to 13 June 1988. A very comprehensive data set was obtained, including surface energy balance data using Bowen ratio and eddy correlation techniques, surface temperature distribution in incomplete canopies, plant biomass and leaf area index, fraction of plant cover, atmospheric optical depth, atmospheric water vapor distribution, and ground- aircraft- and satellite-based reflectance factor measurements. SPOT HRV data were obtained on 11 and 12 June, and Landsat TM data were obtained on 13 June.

A considerable amount of work again went into the study of the effects of atmospheric CO_2 enrichment on plant growth and development. These studies dealt with a number of different types of plants, including two aquatic species, several agronomic and vegetable crops, a native desert succulent and a number of sour orange trees. In all cases, plants grown in the CO_2 enrichment treatments generally did much better than their ambient-grown counterparts, in terms of both above- and below-ground growth. In addition, it was found that CO_2 enrichment was most effective under environmental conditions of solar radiation and air temperature which produced the greatest growth rates in the ambient treatment. Of particular interest were the initial findings of the long-term orange tree experiment. After the first year of the study, the cross-sectional areas of the trunks of the trees in the CO_2 enriched treatment were fully 200% greater than those of the trees in the ambient treatment at a height of two feet above the ground.

Several different studies related to the CO_2 greenhouse effect were also completed. The results of these efforts generally tended to cast doubt upon the conventional wisdom of the day, namely, that a 300 to 600 ppm doubling of the air's CO_2 content will lead to a significant (4.5°C) warming of the Earth. Quite to the contrary, these studies suggest that if there is any CO_2-induced warming at all, it is likely to be fully an order of magnitude less than what is currently predicted by state-of-the-art general circulation models of the atmosphere.

The experiment to investigate the response of winter wheat (*Triticum aestivum* L.) to water and nitrogen fertility treatments under different climatic regimes, was conducted at five locations in the North American Great Plains, from Alberta, Canada to Texas, USA, in 1985 and 1986, was completed. The results were reported in a special issue of Agricultural and Forest Meteorology which was published in 1988.

Jackson, R.D. Surface temperature and the surface energy balance. IN: Proc. Intern. Symp. on Flow and Transport in the Natural Environment: Advances and Applications, W.L. Steffen and O.T. Denmead, eds., Springer-Verlag. Canberra, Australia. Sept. 1987. pp. 133-153.

Surface temperatures, determined from measurements of emitted radiation, can be obtained at scales ranging from a few square millimeters to the global hemisphere. The ability to measure temperatures over large areas has led to the development of techniques for evaluating the surface energy balance at regional scales. In addition to surface temperatures, some techniques require inputs of surface-measured meteorological parameters. Others model the surface fluxes and use a comparison of predicted and measured surface temperatures to keep the models on track. Because of the large scale, validation of the models is difficult. On a smaller scale, it is possible to use both remotely-sensed data and ground-based data to evaluate the energy balance, with validation being somewhat easier. In this review, both regional- and local-scale techniques are discussed. An experiment in which remotely-derived results were compared with Bowen ratio data is described in detail. It is shown that the remote technique will produce adequate values of latent heat flux for uniform surface, but may yield erroneous values for heterogeneous surfaces such as partial canopies.

Jackson, R.D., Slater, P.N. and Moran, M.S. Adjusting for diffuse irradiance on calibrated reflectance panels. Photo-Optical Instrum. Eng. 924:241-248.

Measurements of surface reflectance factors in the field are usually made under conditions of total (direct and diffuse) irradiance. However, the reference panel reflectance factor used to convert the target measurement to reflectance is frequently determined using only direct irradiance. A method for determining the diffuse-irradiance reflectance factor of a calibrated field-reference panel from a knowledge of the direct-irradiance reflectance factor is described. The magnitude of the error involved if only the direct irradiance reflectance factor is known, usually from laboratory calibration, was found to vary from -2% to +5%, depending on zenith angle, atmospheric conditions, and the particular reflectance panel used.

Kustas, W.P., Choudhury, B.J., Inoue, Y., Pinter, P.J., Jr., Moran, M.S., Jackson, R.D. and Reginato, R.J. Ground and aircraft infrared observations over a partially vegetated area. International Journal of Remote Sensing. (in press)

Thermometric observations over a row crop (cotton, <u>Gossypium hirsutum</u> L.) with 20 percent cover using hand-held radiometers were made during several clear days near Maricopa, a town in south central Arizona. A ground sampling routine developed for estimating a composite temperature for the cotton field compared favorably with surface temperatures taken for one day from an aircraft flying at an altitude of approximately 150 m. By considering an equation for the radiative balance at the surface, a

composite surface temperature could be calculated which was within ±1.5°C of the value given by the labor intensive ground sampling method or the aircraft. The data requirements were temperatures of sunlit and shaded soil and sunlit canopy temperature and their respective fractional areas. A model similar to Kimes (1983) requiring only information on row orientation and height and width of the vegetation produced estimates of the fractional areas close to the labor intensive ground measurements. Therefore, it is possible to obtain estimates of the composite surface temperature comparable to low flying aircraft observations over row crops with sparse cover without having to devise a labor intensive ground sampling routine and extensive agronomic measurements and photographs to determine fractional areas of the composite scene.

Huete, A.R. and Jackson, R.D. Soil and atmosphere influences on the spectra of partial canopies. Remote Sensing of Environ. 25:89-105.

A major goal of agricultural remote sensing is to evaluate crop conditions. Such information is an essential for yield prediction and stress detection. During parts of the growing season, some crops do not completely cover the soil. Thus, the soil background influences the remotely sensed data and can cause errors in the inferences of crop condition. The color of the soil background, and whether the soil is wet or dry, determines the degree of influence. Furthermore, the atmosphere interferes with the measurement in that it scatters and absorbs sunlight to a degree determined by the amount of dust and water vapor in the air. This paper examines the influence of different soil backgrounds and different atmospheric conditions on remotely sensed data obtained over partial canopies. It was shown how these factors affect various vegetation measures, and the magnitude of the resulting error if they are ignored.

Holm, R.G., Moran, M.S., Jackson, R.D., Slater, P.N., Biggar, S.F. and Yuan, B. Surface reflectance factor retrieval from Thematic Mapper data. Remote Sensing of Environment. (in press)

Based on the absolute radiometric calibration of the Thematic Mapper (TM) and the use of a radiative transfer program for atmospheric correction, ground reflectances were retrieved from several fields of crops and bare soil in TM bands 1-4 for six TM scenes acquired over a 12-month period. These reflectances were compared to those measured using ground-based and low-altitude, aircraft-mounted radiometers. When, for four TM acquisitions, the comparison was made between areas that had been carefully selected for their high uniformity, the results agreed to ±0.01 (1 σ RMS) over the reflectance range 0.02 to 0.55. When the comparison was made for two of the above acquisitions and two others on different data, for larger areas not carefully selected to be of uniform reflectance, the results agreed to ±0.02 (1 σ RMS), again over the reflectance range 0.02 to 0.55.

Hatfield, J.L., Pinter, P.J., Jr., Cumpton, M.C. and Webb, W.M. Data collection routines on the polycorder for use with infrared thermometers and multiband radiometers. Computers and Electronics in Agric. 2:317-322.

Electronic data capture from portable field instruments improves the efficiency of data collection, minimizes transcription errors, and reduces labor cost by eliminating the time needed to hand-key data into the computer. Two programs have been developed for the Polycorder (Omnidata International) which collect, process, and store analog data from hand-held infrared thermometers and hand-held multiband spectral radiometers. These programs are constructed from subroutines, which serve a number of main programs. Two main segments are used in each program, one for hand-keying of ancillary data associated with the data set and the other for the sampling of the instrument and data processing, e.g., calculation of the sample mean and standard deviation. These programs allow the user to specify the number of experimental plots and whether the standard deviation or coefficient of variation is to be calculated. By simple program modification the number of samples per plot can be changed. Both programs are efficient and all sampling is under direct control of the user.

Moran, M.S., Jackson, R.D., Hart, G.F., Slater, P.N., Bartell, R.J., Biggar, S.F. and Santer, R.P. 1988. Surface reflectance factors from SPOT-1 HRV data at two view angles. IN: Proc. SPOT 1 Image Utilization, Assessment, Results. Paris, France. 23-25 Nov 1987. pp. 1365-1370.

SPOT-1 multispectral and panchromatic data were acquired over an agricultural area on two consecutive days at view zenith angles of +23.0 and -10.7 degrees. Digital data were converted to radiances using the SPOT-1 internal calibrator coefficients. A radiative transfer model, using optical depth data measured on overpass days, was used to calculate surface reflectance factors from the radiances. Differences between satellite-, aircraft- and ground-based surface reflectance factors over bare soil, at the same view and solar zenith angles, were within 0.014. A view angle correction was computed from ground-based measurements of radiance from bare soil at numerous view angles. Satellite-based reflectance values for bare soil, trees, and full cover crops that had originally differed by over 0.09 on the two days were brought to within 0.005 difference in all three XS bands. The correction overcompensated for view angle effects over planar surfaces, i.e., water and roads.

Raymond, L.H., Moran, M.S. and Jackson, R.D. 1988. Mapping evapotranspiration using the energy-based method with remotely sensed data. IN: Proc. Symp. on Water-Use Data for Water Resources Management, M. Waterstone and R.J. Burt (eds.). American Water Resources Assoc. Tucson, AZ. 28-31 Aug 1988. pp. 655-665.

Hourly rates of evapotranspiration, calculated using the energy-budget method with remotely sensed data from the Landsat 5 Thematic Mapper and from aircraft, were mapped over the Maricopa Agricultural Center, Arizona. Evapotranspiration rates calculated using Thematic Mapper data and rates calculated using aircraft data collected on July 23 and on August 8, 1985

were compared over several fields of cotton, alfalfa, and bare soil. Differences between evapotranspiration rates calculated using the two data sources were attributed to differences in pixel size, number, and location Increases in vegetation density corresponded to higher evapotranspiration rates calculated from the aircraft data than from the Thematic Mapper. A comparison of changes in response by the aircraft data from July 23 to August 8 and by the Thematic Mapper data for those dates showed that both data sources could detect differences in evapotranspiration rates over time owing to changes in soil moisture and canopy closure.

Idso, S.B. The CO_2/trace gas greenhouse effect: Greatly overestimated? IN: Proceedings of the Symposium on "Impact of CO_2, Trace Gases, and Climate Change on Global Agriculture, American Society of Agronomy. Anaheim, CA. 27 Nov-2 Dec 1988. (in press)

Most general circulation models of the atmosphere predict that a 300 to 600 μmol CO_2/mol air doubling of the atmospheric CO_2 concentration will increase Earth's mean surface air temperature by about 4°C, and that concomitant increases in certain other trace gases will produce another 4°C warming. Because of a number of demonstrable model deficiencies, however, this conclusion ought not to be accepted as definitive. For one thing, many well-known processes of importance to world climate are not properly represented in the models. A number of other pertinent phenomena are not even included; and the models fail to temper their calculations in accordance with the requirements of certain large-scale empirical constraints. As a result, there is reason to believe that current climate model predictions of the strength of the CO_2/trace gas greenhouse effect may be fully an order of magnitude too large.

Balling, R.C. and Idso, S.B. Historical temperature trends in the United States and the effect of urban population. Journal of Geophysical Research. (in press)

The linear change in temperature between 1920 and 1984 is calculated for 961 station in the conterminous United States. Annual, winter, and summer maps of these temperature changes reveal pronounced geographical patterns, with widespread cooling in the major south-central portion of the United States and general warming in the Northeast and West. Stepwise multiple regression analysis identifies a statistically significant impact of population change on these temperature trends, even though the stations utilized in this study had a median population of only 5,600 in 1980. Both the observed mean annual cooling of the country and the warming bias provided by these small urban centers suggest that we may not yet have a proper perspective on global climatic change.

Idso, S.B. Carbon dioxide, soil moisture, and future crop production. Soil Science. (in press)

Model simulations of the effects of increases in atmospheric carbon dioxide on air temperature, precipitation and soil moisture suggest that the resultant "greenhouse effect" will be bad for agriculture. Experimental evidence, however, indicates otherwise, demonstrating that

plants can more than compensate for the predicted adverse climatic changes. Indeed, recent evidence from around the globe suggests that a carbon dioxide-induced stimulation of the biosphere is already in progress.

Idso, S.B. The three stages of plant response to atmospheric CO_2 enrichment. Plant Physiol. Biochem. (in press)

Weekly assessments of biomass production in water hyacinths and daily assessments of new-leaf production in water lilies demonstrate that the positive effects of atmospheric CO_2 enrichment on growth rates of these plants are considerably greater both before (I) and after (III) the primary maximum-growth-rate stage (II) characteristics of the middle portion of a plant's life cycle. For these two particular aquatic macrophytes, the growth enhancement factor for a 300 ppm increase in the atmospheric CO_2 concentration went from a mean of 1.54 in stage I, to 1.33 in stage II, to actually approach infinity in stage III.

Idso, S.B., Allen, S.G., Anderson, M.G. and Kimball, B.A. Atmospheric CO_2 enrichment enhances survival of <u>Azolla</u> at high temperatures. Environmental and Experimental Botany. (in press)

In two years of experimentation with <u>Azolla</u> <u>pinnata</u> var. <u>pinnata</u> at Phoenix, Arizona, growth rates of this floating aquatic fern first decreases, then stagnated, and finally became negative when the mean air temperature rose above 30°C. When the atmospheric CO_2 content above the plants was increased from the mean ambient concentration of 340 μmol CO_2 mol^{-1} air to 640 μmol CO_2 mol^{-1} air, however, the debilitating effects of high temperatures were reduced: in one case to a much less severe negative growth rate, in another case to merely a short period of zero growth rate, and in a third case to no discernible ill effects whatsoever--in spite of the fact that the ambient treatment plants in this instance all died. With the double verification of this phenomenon provided by both weekly biomass and periodic net photosynthesis determinations, it would appear that atmospheric CO_2 enrichment may be capable of preventing the deaths of some plant species in situations where their demise is normally brought about by either the direct effects of unduly high temperatures or by associated debilitating diseases.

Idso, S.B. and Kimball, B.A. Growth response of carrot and radish to atmospheric CO_2 enrichment. Environmental and Experimental Botany. (in press)

Seven crops of carrots and eleven crops of radishes were grown from seed in open-top, clear-plastic-wall, CO_2-enrichment chambers throughout the entire year at Phoenix, Arizona. Cumulative dry matter production at weekly intervals was significantly increased by a 300 ppm increase in CO_2 content of the air at all temperatures encountered, but with progressively greater effects being registered at higher and higher temperatures. At 25°C, the productivity enhancement factor for radish was about 1.5, while for carrot it was approximately 2.0. When regressed upon air temperature, the productivity enhancement factors of both species decreased to a null

value of 1.0 in the vicinity of 12°C. The slope of the carrot relationship was nearly 250% greater than that of the radish relationship.

Idso, S.B., Allen, S.G., Kimball, B.A. and Choudhury, B.J. Problems with porometry: Measuring net photosynthesis by leaf chamber techniques. Agronomy Journal. (in press)

Prior experiments with cotton (Gossypium hirsutum L.) and water hyacinth (Eichhornia crassipes (Mart.) Solms) demonstrated that porometer chamber conditions may significantly perturb the measurement of leaf stomatal conductance. This study was thus conducted to determine if net photosynthesis rate measurements of water hyacinth and cotton leaves were similarly perturbed by leaf chamber conditions, and if so, to devise a method to correct for the instrument-induced error. Several net photosynthesis rate and concurrent canopy environmental data sets for these two plants at Phoenix, AZ were analyzed within the context of the non-water-stressed baseline paradigm, which relates foliage-to-air temperature difference to air vapor pressure deficit. It was found that leaf-chamber measurements of net photosynthesis rate were subject to the same type of measurement error as that associated with porometer measurements of leaf stomatal conductance. For plants transpiring at potential rates, photosynthesis rates can be corrected by use of ancillary data obtained by the leaf-chamber system. However, the proper adjustment of net photosynthesis rates of water-stressed plants measured with leaf chambers required free-air foliage and air temperatures, as well as the free-air humidity. It was thereby demonstrated that concurrent infrared radiation thermometry, as well as simultaneous measurements of air wet- and dry-bulb temperatures, are required to correctly evaluate (by leaf chamber techniques) the net photosynthesis rates of plants which are experiencing any degree of stomatal closure due to some aspect of their normal environment.

Idso, S.B. The CO_2 greenhouse effect on Mars, Earth, and Venus. The Science of Total Environ. 77:291-294.

A simple comparative analysis of the mean surface air temperatures and atmospheric pressures and compositions of Mars and Venus suggests that the greenhouse warming due to a 300-600 ppm doubling of the CO_2 concentration of Earth's atmosphere should be only about 0.4°C. The legitimacy of this conclusion is supported by several independent considerations.

Idso, S.B. Three phases of plant response to atmospheric CO_2 enrichment. Plant Physiol. 87:5-7.

Several years of research on seven different plants (five terrestrial and two aquatic species) suggest that the beneficial effects of atmospheric CO_2 enrichment may be divided into three distinct growth response phases. First is a well-watered optimum-growth-rate phase where a 300 parts per million increase in the CO_2 content of the air generally increases plant productivity by approximately 30%. Next comes a nonlethal water-stressed phase where the same increase in atmospheric CO_2 is more than half again as effective in increasing plant productivity. Finally, there is a water-

stressed phase normally indicative of impending death, where atmospheric CO_2 enrichment may actually prevent plants from succumbing to the rigors of the environment and enable them to maintain essential life processes, as life ebbs from corresponding ambient-treatment plants.

Idso, S.B. Carbon dioxide and climate in the Vostok ice core. Atmospheric Environ. 22:2341-2342.

Analyses of the CO_2 temperature and dust characteristics of the Vostok ice core, combined with recent analyses of marine phytoplanktonic growth rates, suggest that variations in atmospheric CO_2 concentration have not played a significant role in the waxing and waning of past ice ages, and that the Vostok data, therefore, do not provide support for the magnitude of CO_2 greenhouse warming predicted by current theory.

Idso, S.B. Development of a simplified plant stomatal resistance model and its validation for potentially transpiring and water-stressed water hyacinths. Atmospheric Environ. 22:1707-1713.

A simple method of upper-canopy plant stomatal resistance (r_{uC}) was developed which requires but four input parameters: canopy aerodynamic resistance, upper-canopy foliage temperature, and air vapor pressure deficit and temperature. The model was tested against upper-canopy sunlit leaf stomatal resistance (r_L) measurements of both potentially and non-potentially transpiring water hyacinth plants over the upper-canopy-intercepted net radiation range of 300-450 W m^{-2} and over a 10-fold range of r_L. In all instances, and indicative of the model's good performance, the ratio of r_{uC}/r_L consistently averaged about 1.25, due to partial self-shading of the upper-canopy foliage. The significance of this finding to air pollution studies arises from the facts that (1) contemporary knowledge of a plant canopy's leaf area index would allow the transformation of r_{uC} to r_C, the total canopy diffusive resistance, and (2) the proper accounting for different trace gas diffusivities would allow the transformation of r_C for water vapor to the variety of r_C values required to infer the gaseous deposition of important pollutant gas species at vegetated surfaces.

Idso, S.B. and Allen, S.G. Problems with porometry: Measuring stomatal conductances of potentially transpiring plants. Agric. For. Meteorol. 43:49-58.

Porometer measurements of the stomatal conductances (C_s) of potentially transpiring water hyacinth plants at Phoenix, Arizona in October of 1984, May-June of 1985, and September of 1986 indicate that C_s steadily drops as the vapor pressure deficit (VPD) of the air in the measuring system's cuvette or leaf chamber rises. Utilizing this relationship to calculate the foliage-air temperature differential (T_F - T_A) response of these leaves to leaf-chamber air VPD, as per the basic equations of standard heat and water vapor transport theory, we obtain a leaf-chamber "non-water-stressed baseline" that is consistent with leaf-chamber measurements of T_F - T_A vs. air VPD. Free-air T_F - T_A vs. air VPD data, on the other hand, produce a relationship that is similarly consistent with a plant

stomatal conductance which is invariant with respect to the air VPD. Hence, we conclude that the very act of stomatal conductance measure-ment alters a potentially transpiring plant's evaporative water loss rate in such a way that, for very high air VPD conditions, the directly measured C_s value (although correct for the leaf in the cuvette or leaf chamber) may be much reduced from that characteristic of comparable non-chamber-encumbered plants in the free air. We then demonstrate that this instrument-induced reduction in directly measured C_s values is a unique function of the leaf-chamber IJ index, evaluated with respect to the plant's free-air non-water-stressed baseline. Similar results obtained by others for cotton suggest that this phenomenon may be quite general, and that the C_s vs. air VPD interaction, believed by many to be widely operative throughout the plant kingdom, may not really exist in actual field situations.

Allen, S.G., Idso, S.B., Kimball, B.A. and Anderson, M.G. Interactive effects of CO_2 and environment on photosynthesis of Azolla. Agric. For. Meteorol. 42:209-217.

The aquatic fern Azolla pinnata was grown out of doors between 26 September and 10 May 1986 in open-top CO_2 enrichment chambers continuously supplied with either 640 or 340 μl CO_2 l^{-1} air in order to examine the interactive effects of atmospheric CO_2 concentration with other environmental variables on net photosynthesis. Net photosynthesis was influenced by significant interactions between CO_2 level and short-wave solar radiation ($P < 0.01$) as well as air temperature ($P < 0.01$). Net photosynthesis was approximately equal for Azolla grown in the two CO_2 treatments during conditions of low light intensity and low temperature. Under the more favorable conditions of high light intensity and high temperature, the net photosynthesis rates of the Azolla in the high CO_2 treatment were as much as 70% greater than for those in the low CO_2 treatment. Minimum air temperatures had a greater effect on net photosynthesis than maximum temperatures in both the high and low CO_2 treatments. Net photosynthesis in 340 μl CO_2 l^{-1} air was influenced more by air temperature than by solar radiation, while solar radiation had the greater effect on net photosynthesis in 640 μl CO_2 l^{-1} air.

Idso, S.B. and Anderson, M.G. A comparison of two recent studies of transpirational water loss from emergent aquatic macrophytes. Aquatic Bot. 31:191-195.

Data from two recent studies suggest that large expanses of short water hyacinths tend to reduce the amount of water which would normally be lost by evaporation from the surfaces of sizable water bodies, but that tall water hyacinths tend to enhance evaporative water losses from such surfaces. For cattails, however, more evidence is needed before any similar conclusion may be reached.

Idso, S.B., Kimball, B.A. and Mauney, J.R. Atmospheric CO_2 enrichment and plant dry matter content. Agric. For. Meteorol. 43:171-181.

Fresh and dry plant weights were measured throughout a number of different CO_2 enrichment experiments with six terrestrial plants and two aquatic species. Similar data were also extracted from the literature for 18 additional plants. In general, CO_2 enrichment had little effect on plant percentage dry matter content, except under conditions conducive to starch accumulation in leaves, and then it caused an increase in percentage dry matter content.

Maracchi, G., Zipoli, G., Pinter, P.J., Jr., and Reginato, R.J. Water stress effects on reflectance and emittance of winter wheat. IN: Proc. 8th EARSeL Symp., Alpine and Mediterranean Areas: A Challenge for Remote Sensing. Capri (Naples), Italy. 17-20 May 1988. pp. 3-13.

A large scale field experiment was conducted in undulating terrain of central Italy during 1986. The objective was to determine the utility of several remote sensing techniques for detecting water stress in winter wheat (Triticum aestivum, var. MEC). Canopy reflectance and emittance were measured in five Thematic Mapper waveband intervals using ground-based instrumentation. A temperature-based stress index showed high sensitivity to the onset of plant water stress and was well-correlated with physiological measurements of water status. Radiant canopy temperatures were only slightly influenced by topography. By contrast, field slope and aspect had a strong influence on the diurnal behavior of single band reflectance factors and linear vegetation indices (VIs) such as Greenness. Spectral VIs which ratioed near infrared and visible reflectances were less influenced by topography and remained well-correlated with green biomass of the canopy. This sensitivity permitted detection of a drought-related decline in biomass several days after the temperature-based index first detected the onset of stress.

Reginato, R.J. Surface energy flux measurements and reflectance factors using satellite-, aircraft-, and ground-based instrumentation. IN: Proc. 21st Intern. Symp. on Remote Sensing. Ann Arbor, MI. 26-30 Oct 1987. pp. 393-399.

Knowledge of the type and amount of vegetation covering agricultural fields and the amount of evapotranspiration from those surfaces will greatly assist farm supervisors in managing their water resources more efficiently. For timely management decisions, it is necessary to make these assessments quickly over large areas, and remote sensing technology offers a solution. To evaluate the accuracy of these types of measurements, a week-long field experiment was conducted in June 1987 to assess the energy flux and spectral reflectance distribution both spatially and temporally over several agricultural fields. The energy flux components of interest were latent heat (evapotranspiration) and sensible heat. These were evaluated at ground level with four Bowen ratio systems, with four eddy correlation units, and with a tethered balloon radiosonde system. Also, four-band and eight-band radiometers along with appropriate micrometeorological data were used to estimate fluxes.

Radiometers were mounted in an aircraft to measure reflected and emitted radiation from selected agricultural fields. Landsat TM data were scheduled but not obtained due to clouds. SPOT data were obtained on two successive days. Atmospheric optical depth measurements allowed satellite based reflectance factor data to be compared with aircraft and ground-based reflectance factors for bare soil and agricultural crops The 27 participants, who represented seven departments from five universities, six offices from three federal agencies, two private institutions and one foreign agency were funded by their respective organizations for their part in the overall experiment.

Reginato, R.J., Hatfield, J.L., Bauer, A., Hubbard, K.G., Blad, B.L., Verma, S.B., Kanemasu, E.T. and Major, D.J. Winter wheat response to water nitrogen in the North American Great Plains. Agric. For. Meteorol. 44(2):105-116.

A unique, identical experiment was conducted at five locations in the North American Great Plains, from Alberta, Canada to Texas, USA, in 1985 and 1986, to investigate the response of winter wheat (Triticum aestivum L.) to water and nitrogen fertility treatments under these climatic regimes. The experimental design consisted of four nitrogen levels, three irrigation regimes, two cultivars, with four replications. One cultivar, Colt, was common to all locations. Crop response throughout the growing season was monitored by intensive plant sampling, measuring spectral reflectance, evaluating canopy temperature, and by detailed measurements of the microclimate and of soil water content. This paper discusses the procedures common to all locations.

Reginato, R.J. and Jackson, R.D. Remote sensing of water use by agricultural crops and natural vegetation. IN: Proc. USCID Regional Meeting on Water Management. Denver, CO. 2-4 Sept 1987. pp. 325-335.

Water loss from soil and vegetation was evaluated from agricultural crops and an arid ecosystems using a combination of remotely sensed and ground-based data. This information was used in the energy balance equation, and eddy correlation systems. An analysis demonstrated that when the vegetation cover was near complete, calculations of evapotranspiration (ET) agreed well with field data, but when the vegetation was sparse, the agreement was poor. Empirically derived coefficients, based on fractional plant cover and plant height brought the results of the two techniques closer together. The data demonstrate the shortcomings of the theoretical approach in estimating ET over areas of partial vegetation, and where additional research is needed in order to solve the problem. Before remote sensing techniques can be used confidently over large areas to estimate ET, existing theory must be modified or new theory developed.

MACIII

Introduction

The third major remote sensing experiment at the University of Arizona's Maricopa Agricultural Center (MAC III) was conducted during the period 10 to 13 June 1988. Prior to MAC III, two other remote sensing experiments had been conducted at the Center. MAC I was a long term (15 month) experiment designed to obtain concurrent Landsat-5 Thematic Mapper (TM) and radiometric data from a low altitude aircraft every TM opportunity (Landsat-5 has a 16 day repeat cycle) from April 1985 to June 1986. Of 28 possible TM scenes, 12 were obtained. This experiment provided the data for the first quantitative calculation of reflectance factors using satellite data. This result required a knowledge of satellite sensor calibration factors and an accurate evaluation of atmospheric scattering and absorption. Other than atmospheric optical depth measurements, relatively few ground data were collected during this experiment.

MAC II, conducted from 9 to 14 June 1987, was much shorter in time, but much more intensive in data collection. Although MAC I was a multi-agency cooperative effort, MAC II involved many more research groups. Twenty seven researchers from 16 organizations participated. The ground rules were that interested parties were welcome, provided that they actively participate in the experiment and prepare a report on their results. The reports were bound and distributed to all participants with the caveat that the data not be shared with non-participants for a period of one year, thus allowing time for the participants to prepare papers on their work before further dissemination of the report.

The large number of participants resulted in a very comprehensive data set. The data set included surface energy balance data using Bowen ratio and eddy correlation techniques, surface temperature distribution in incomplete canopies, plant biomass and leaf area index, fraction of plant cover, leaf angle and distributions. In addition to the atmospheric optical depth measurements, ground reflectance measurements were made in a pattern such that the results could be readily compared with the low altitude aircraft and satellite data, thus providing a ground, aircraft, satellite link from which to compare reflectance factor data. Radiosonde measurements were made to characterize the water vapor distribution in the atmosphere. A Landsat-5 TM overpass occurred on 11 June but clouds precluded ordering the tapes. SPOT data were obtained on 13 and 14 June. Both days were cloud free. Low altitude aircraft data were obtained only on 14 June.

MAC III was similar to MAC II in many respects, with the same ground rules for participation applying. There were more participants and more research groups involved. As with MAC II, each research group was responsible for their own funding, as no outside funds were sought or received.

The experiment centered around the period 10 to 13 June 1988. SPOT satellite overpasses occurred on 11 and 12 June, and Landsat TM on the 13th. Weather conditions during these 3 days was excellent -- clear and hot. Data were obtained with an aircraft-based Daedalus scanner at altitudes of 305 and 4572 m on 11 June. Spectral data were collected from low-level aircraft flights on all three days. Aircraft instrumentation consisted of an infrared thermometer with a 15° field-of-view (fov), a 4-band radiometer with SPOT or TM filters with a 15° fovs, a color video camera to record the areas where the spectral and thermal data were taken, and a data logger to record the data from the radiometers. The speed and altitude of the aircraft and the scan rate of the data logger resulted in 35 to 40 observations (about 40m in diameter) along a 1.6 km path.

Optical density measurements of the atmosphere were taken from sunup to solar noon on the three primary days to provide corrections to satellite data for the atmospheric conditions at overpass times. Ground reflectance data were collected over bare soil and cotton for comparison with aircraft and satellite data. An 8-band multi-modular radiometer with TM filters and a 4-band radiometer similar to that mounted in the aircraft were mounted on a backpack-type carrier. The radiometers were maintained in a nadir position over a series of transects covering a 16 x 4 pixel area. Other 4-band radiometers were used to obtain data from a nadir orientation over cotton and alfalfa fields, and from an angular orientation over cotton. A radiometer was mounted on a device which allowed reflectance measurements from view angles ranging from -45 to + 45 degrees over soils have 3 different roughness characteristics. The latter information was to assess bidirectional reflectance and to simulate the SPOT view angles.

Soil and plant properties were evaluated before, during and after the 3-day experiment. Soil water content was measured in several fields to investigate the spatial and temporal distribution of water within the root zone and at the soil surface, and to determine whether or not remotely sensed parameters could be used to characterize the water regime. Soil heat flux, soil temperature and net radiation were measured continuously under cotton, alfalfa and smooth, dry, bare soil to evaluate how remote measurements might be used to evaluate soil heat flux. Plant and soil temperatures were measured with hand-held infrared thermometers on an cotton field having a partial canopy. These measurements were a continuation of the investigation started in MAC II. Plant samples of cotton and alfalfa were taken before and after the experiment to characterize plant conditions at the time of satellites overpasses. Photosynthesis measurements were taken frequently on stressed and non-stressed cotton using a chamber technique. An optical technique based on intercepted solar radiation was used to calculate the leaf area index of cotton.

Latent heat flux was evaluated over dry, bare soil (medium rough surface), cotton and alfalfa utilizing 4 eddy correlation systems and 4 Bowen Ratio units. These instruments were placed over the various surfaces such that they would be included in the areas observed from the aircraft sensors.

Two techniques, new to the MAC experiments, were evaluated during the 3-day period. A truck-mounted LIDAR unit was used to determine the atmospheric water content over cotton and bare soil surfaces along a 500 meter pathlength about 2-3 m above the soil surface. Over a shorter path (100-200 m) a FTIR system was used to measure the quantity of several gases, including water vapor and carbon dioxide. The potential use of these data will be to rapidly evaluate the spatial variability of ET and photosynthesis over various surfaces.

Participants in MAC III represented the following institutions:

U. S. Department of Agriculture, Agricultural Research Service
- Water Conservation Laboratory, Phoenix, AZ
- Hydrology Laboratory, Beltsville, MD
- Remote Sensing Laboratory, Beltsville, MD

U. S. Department of Interior, Geological Survey
- Water Resources Division, Phoenix, AZ
- Water Resources Division, Tucson, AZ
- Water Resources Division, Carson City, NV

University of Arizona
- Agricultural Engineering Department, Tucson, AZ
- Maricopa Agricultural Center, Maricopa, AZ
- Optical Sciences Center, Tucson, AZ
- School of Renewable Natural Resources, Tucson, AZ
- Soil and Water Science Department, Tucson, AZ

Massachusetts Institute of Technology
- Parsons Laboratory, Cambridge, MA

New Mexico State University
- State Climatological Laboratory, Las Cruces, NM

Los Alamos National Laboratory
- Environmental Science Group, Los Alamos, NM

San Diego State University
- Department of Geography, San Diego, CA

University of New Mexico
- Department of Biology, Albuquerque, NM

Pacific Northwest Laboratory
- Department of Environmental Sciences, Richland, WA

CSIRO
- Center for Environmental Mechanics, Canberra, Australia

EG&G Energy Measurements, Inc.
- Multispectral Remote Sensing Department, Las Vegas, NV

PERSONNEL

R. J. Reginato, R. D. Jackson, S. B. Idso, P. J. Pinter, Jr., M. S. Moran T. R. Clarke, R. S. Seay, S. M. Johnson, C. E. McGuire, B. L. Murphy.

TITLE: CANAL SYSTEMS OPERATIONS PROJECT

SPC: 1.3.03.1.d CRIS WORK UNIT: 5422-20740-013

Introduction

In 1988 the Canal Systems Operations Project made progress on several fronts. Monitoring operations in the Wellton-Mohawk Irrigation and Drainage District (WMIDD) were completed and the equipment was mothballed for future use. A computer program for modeling free-surface hydraulic networks was purchased. Visiting scientist Dr. Wayne Clyma began a sabbatical from Colorado State University at the USWCL in August. Project personnel were exposed to important management principles through his contributions. The highlight of the year was a *rapid Diagnostic Analysis* of the WMIDD and the resulting new understanding of district and farm operations.

Canal Monitoring Studies

On December 15 the last set of eproms was collected from the data loggers which had been monitoring operations of the WM17.0 and M42.9 laterals in the WMIDD since 1985. These were the 65th and 26th data sets, respectively, collected from the two laterals, each representing about three weeks of readings. The equipment operated satisfactorily during the year, with fewer of the pump failures, electronic glitches and district maintenance problems that characterized previous years.

At sites throughout the monitored reaches of canal, silting of broad-crested weirs and long-throated flumes was a persistent problem. Most of the material apparently falls in from the canal banks, and consolidates when the canal is ponded or empty, eventually giving rise to grasses and other vegetative matter. Several attempts were made to clean the flumes by hand using shovels: very hard work. Technicians Padilla and Gerard have now developed a technique for suspending a high-pressure water jet nozzle from a portable bridge, which loosens the deposits and moves them downstream. This technique is effective only when there is sufficient flow over the flume to carry the material away.

After monitoring was stopped, the air-bubbler tubes at each instrument site were disconnected from the flow control and three-way valves, bundled and left on-site in weather-proof, padlocked boxes. Bubblers were left in place on gates and canal banks in case additional monitoring is desired in the future. Data loggers, pumps and valves, still attached to plywood bases, were returned to the USWCL. The instrument packages were cleaned, tested, and stored.

Raw data for the monitoring project have been stored on DC600A magnetic tape cartridges, except for the last few data sets which are stored on high density 1.2Mb floppy disks. Data processed through the "column stripping" stage (Fortran program CDBW and derivatives) and monthly delivery statistics reports are also stored on tape cartridges. All of this archive material is stored in the USWCL vault. Data from further

down the processing stream are found variously in files on the "D" drive of Palmer's 286 machine, and on "system backup" tape cartridges for this machine.

Data analysis continued, by examination of plots of all flow activity along the monitored laterals for several week-long periods. Such examination showed the slight but nevertheless present impact of main canal levels on flows into the WM17.0, and that weekend deliveries occur frequently, contrary to district assertions. Fluctuating flow rates are ubiquitous and appear connected to the amount of activity along the canals.

A beginning was made to correlating water orders and bills with the monitored deliveries. It appears that orders are usually for more water than is actually desired, which may be a consequence of district rules that provide no penalty for over-ordering of water. Due to fluctuating flows and limited flow measurement by ditchriders, the water bill for a particular delivery may be quite different than the true average. Thus, controlling fluctuations may be as important to district water accounting as to on-farm water management.

Canal Hydraulic Modeling

Principally on the basis of John Parrish's researches at the USWCL in 1987, a decision was made to purchase the CARIMA computer model. CARIMA, developed by the French firm SOGREAH (now LHF) to model sewer pipe networks and large river systems, allows solution of one-dimensional flow problems for canal networks of any size and complexity, with hydrologic and regulatory inputs. The Iowa Institute of Hydraulic Research (IIHR) at Iowa City is the U.S. distributor for the model, and the purchase price included training by the IIHR's Dr. Forrest Holly who wrote much of the CARIMA code while employed by SOGREAH. At the end of calendar 1988, delivery of the model and training had not yet taken place.

Discussions with Dr. Francis Gichuki about the Utah State Model (USM) for canal networks indicated a number of situations where CARIMA might be expected to provide more realistic solutions. But it is also clear that simpler models, especially with attractive interfaces such as the USM, need to be calibrated and tested for those situations they are fully capable of handling. CARIMA, as a full-function general model, might provide a standard against which other models could be contrasted.

Diagnostic Analysis and Management Planning

Management planning is a process developed for business management, and adapted for use with irrigated agricultural systems by the Water Management Synthesis Project of Colorado State University, under contract from the U.S. Agency for International Development. The management planning process provides a framework for examining a system's design, objectives, performance and trajectory, in a structured, self-conscious manner that establishes objectivity and increases understanding of the

system by the planning team members. That objectivity and understanding is the basis for setting priorities among competing goals and performance levels, and for implementing proposed improvements.

Central to the effectiveness of management planning is diagnostic analysis (DA), a process for synthesizing an increased, interdisciplinary understanding of system performance. This new understanding is achieved by team efforts which identify areas of high and low performance, and compare current with designed or desired performance levels.

Our exposure to management planning and diagnostic analysis has been primarily due to Dr. Clyma's efforts starting in August 1988. His transfer to us of these ideas came about through a series of discussions concerned with irrigated agriculture at large (August to November), then through a trial DA in the WMIDD (November and December).

MANAGEMENT PLANNING: The management planning process for an irrigation district has been described (Dedrick and Clyma, 1989) as several sequential phases of activity, with the overall purpose of improving the performance of the district while conserving water and improving services to farmers to sustain effective irrigated agriculture:

Phase I - Overall Planning

A workshop is conducted which establishes: the context and needs of the district subsystems under consideration; the purpose of and objectives for the entire management planning effort; and the roles and responsibilities of the team members. The planning team should consist of those who will have responsibility for implementing improvements, as well as technical consultants and farmer representatives. A management specialist to facilitate the workshop may be very helpful for maintaining balance amongst competing interests, and for seeing that agendas are followed. An interdisciplinary approach to team formation will help insure that important factors impacting performance are not overlooked by, say, an engineering-only view of the system. An overall plan for all remaining phases, and a detailed plan for Phase II are the important outcomes of the overall planning phase.

Phase II - Diagnostic Analysis

A profound understanding of the performance of the system (facilities and management) is sought through study of background material and new information. Such an understanding is the basis for identifying the most important aspects of performance and making the appropriate responses. See the discussion below regarding Rapid Diagnostic Analysis. Team members for this phase will consist of some or all of the Phase I team, with additions or subtractions as appropriate to collect and analyze the required data.

Phase III - Opportunity Definition

The opportunity definition phase also takes the form of a workshop, organized to allow interdisciplinary team members to reach a common understanding of the performance of the district and the factors that contribute to the high and low performance. This understanding is based upon the results of the DA, and on the knowledge and experience of the workshop participants. The outcomes of phase III are the identification of improvement priorities and general strategies for accomplishing the improvements. The entire phase I team should be involved in the opportunity definition phase, as well as other district managers, farmer representatives, and personnel from other interested organizations as appropriate.

Phase IV - Problem Solving and Planning

In this phase, district operational managers, farmer representatives and personnel from other involved organizations meet to set goals for improvement, define objectives and plan activities necessary for improved performance of the system. Roles and responsibilities for specific activities, time frames, and monitoring and evaluation plans are established. The principal output of the problem solving and planning phase is a management plan to guide improvement implementation and evaluation.

Phase V - Finalization of Plans

During this phase, the management plan written during the problem solving and planning phase is made available for review by all concerned persons and organizations, including senior district management and farmer or rights holders boards. Public meetings may be organized to discuss the plan. Comments are reviewed and incorporated as appropriate. The outcome of this phase is approval of a final management plan at the highest required administrative level. Team membership for this finalization phase should include representatives of senior district management, district boards, and farmer, research and extension organizations.

Phase VI - Review / Replanning of Management Plan

Some time after the management plan has been implemented (perhaps six months or a year), a replanning team is convened to review progress under the new plan. The original planning team and appropriate outside consultants should comprise this team, which on the basis of new information or monitoring and evaluation results suggests redirection of present management efforts and reconsiders improvements and their priorities. The output of this phase would be a revised management plan.

Obviously, the replanning should not end with a single cycle, but with conscientious management can be repeated and eventually institutionalized. The entire management planning process can be applied recursively to the

various subsystems of irrigated agriculture within a project area, to eventually achieve improvements in many aspects of district performance.

As a first attempt at introducing these ideas to the group, we attempted to apply the management planning process to the canal systems operations project, our group research program, and the ARS irrigation research program *in toto*. Our objectives were to come to some new understandings of irrigation systems and irrigation development, and to develop an agenda of research priorities as a result.

The objective of water delivery system management was seen to be the same as the objective of irrigated agriculture: to produce a sustainable agriculture for more people, and/or different crops, and/or greater yield than would otherwise be possible in the project area. <u>Measurable</u> outcomes of water delivery system management, agreed upon by the group, were: high on-farm water use efficiencies; high conveyance efficiencies; reasonable economic returns for on-farm investments; low cost and easy to manage delivery systems; water delivery not in conflict with farm water requirements; production adequate to pay for construction and maintenance; and a generally improving performance of the system. Yet few of these measures are made or used in managing existing systems.

The lack of objective performance measures was thus identified as a serious constraint to high quality water deliveries. Performance measures require known physical quantities, and knowledge of the desired and possible response of the system. Ratios between designed, intended and required flow parameters (rate, volume, frequency, etc.) were identified which measure their dependability, adequacy and equity over space and time (Mohammed and Clyma, 1988). Clemmens (1988) subsequently expanded this treatment of performance measures with a statistical approach to designing and operating canal systems at a predetermined performance level. Ultimate performance goals for delivery systems were determined to include demand delivery, idiot-proof operations, and a supply that is not limiting.

While examining the factors that cause poor performance of irrigated agriculture projects, it became clear that thorough design and operation of such projects require an interdisciplinary approach, utilizing at least the talents of economists, sociologists, engineers, soil scientists, agronomists and farmers. The irrigation project is not simply an engineering work superimposed on an area, but a complex of physical facilities, native and external socio-economic matrices, and cooperative and authoritarian water supply and delivery organizations.

Serious differences in definitions and concepts about irrigated agriculture were revealed among the several of us involved in the discussions (Palmer, Clyma, Dedrick and Clemmens). Consensus about overall research mission (coordination with research agenda, achievement of client expectations) was not forthcoming. It was decided that an overall analysis and rethinking of research in irrigated agriculture was more than the group wanted to attempt under present circumstances. So to make the time Dr. Clyma was at the USWCL more productive, the group took a different tack, and decided to attempt a rapid diagnostic analysis of the WMIDD as a more concrete example of the management planning and DA processes.

RAPID DIAGNOSTIC ANALYSIS: Diagnostic analysis is defined by Lowdermilk, et al. (1983) as an interdisciplinary method for examining an operating irrigation system with its interrelated components. The objectives of diagnostic analysis are: 1) to understand the operating irrigation system so as to recognize both its values, good features and benefits, as well as its constraints to efficient operation; and 2) to assign the constraints a priority for consideration of improvements. Like management planning, the DA process can be considered as several phases:

Phase I - Setting Preliminary Objectives

During this phase, a first attempt is made to define the objectives of the diagnosis. These objectives would commonly include: a profound understanding of the actual irrigation system and its areas of high and low performance; the identification of major physical, biological, economic and organizational constraints to sustained agriculture; and the assigning of priority to these constraints so as to assist the development and assessment of possible solutions.

Phase II - Reconnaissance

Reconnaissance is the initial survey of an irrigation system, used to quickly examine the entire system as it operates, while looking for both positive and negative aspects. This survey should be an overview of the multiple dimensions of the system: engineering, sociological, economic, agronomic. Based on the reconnaissance, the general objectives established in phase I may be refined or priorities reordered. The purpose of reconnaissance is to enable the DA team to conduct detailed studies based on the realities of the system rather than supposition.

A successful reconnaissance, according to Lowdermilk, et al. (1983) consists of seven steps: 1) setting objectives; 2) allocating responsibility; 3) collecting information; 4) developing work plans; 5) collecting data (interviews and measurements); 6) analyzing data and synthesizing understanding; and 7) report writing.

Phase III - Revised Objectives and Plans

After reconnaissance of the system, the team will be in a position to revise plans for the remaining phases of the diagnosis. New hypotheses are developed based on new information. Initial objectives may be found to have been inappropriate and in need of reformulation. Interview questions and techniques may be revised on the basis of testing during reconnaissance. A complete plan for the Detailed Studies is the important outcome of this phase.

Phase IV - Detailed Studies

Depending on the scale of the investigation and the system under study, detailed studies of system performance may take from a few days up to one or more cropping seasons. The objectives of the

detailed studies are the same as the revised objectives for the entire diagnostic analysis. This phase is similar in structure to the reconnaissance phase: objectives are set; responsibility is allocated; formal field studies are conducted; data are analyzed; and disciplinary reports are written.

The actual activities will be more focused and more of a single-discipline nature than the reconnaissance studies. Data should be analyzed while the study is still underway, so that mistakes in methodology can be detected and corrected, and changes in direction can be accommodated without a lot of wasted effort. The entire interdisciplinary team should meet at regular intervals during the detailed studies phase, to share findings and to revise objectives and schedules.

Phase V - Interdisciplinary Analysis and Synthesis

During this very important phase, team members from the different disciplines meet to examine the various components of the system, then synthesize their individual results so that the exact causes of low and high performance of the system can be substantiated with results of the detailed studies. By analysis the system is conceptually taken apart, by discipline, function or component. It is examined, discussed, deeply thought about, then put back together. Synthesis results in an interdisciplinary understanding of the system and its possible improvement. Principal system constraints are identified for the purpose of developing improvements. Alternative solutions to problems are given priorities. The team identifies the benefits to be obtained from recommended improvements, and where or upon whom the benefits will accrue. The team also identifies areas of high performance, which can be as valuable for managing the system as knowledge of low performance areas.

Phase VI - Report Writing

The report writing phase is concurrent with analysis and synthesis, and will generally result in a disciplinary report, and an interdisciplinary report. The disciplinary report draws on the detailed studies reports, and its conclusions are the basis for the interdisciplinary report. The interdisciplinary report should stress the whole-system perspective, the interdisciplinary approach to the DA, and the involvement of farmers. This report should not simply be parallel treatments of the disciplinary findings (a multidisciplinary report), but should reflect the mutually interdependent components of the system, and the team's common understanding of the system's performance. The report should be carefully written, as it has the potential to become a starting point for future improvements, be they structural, organizational, or plans for long-term action research.

As is the case for the management planning process, the diagnostic analysis process can be applied at any scale to examine any aspect of a system at any level of detail. If the basic structure is followed, the team members are virtually guaranteed to emerge from the process more informed about and able to impact the performance of the system, no matter how abbreviated the effort.

Notice that the steps for the reconnaissance phase are very similar to the steps for the overall DA, and in fact the reconnaissance can be considered a rapid diagnostic analysis. Due to time and staff constraints, and to our principal objective of learning the process, a rapid DA of the WMIDD was organized which followed approximately the steps described above under Phase II - Reconnaissance. In practice, the first steps of determining objectives, allocating responsibility and developing work plans and methods tended to merge. Implied decisions produced some confusion as the team (Palmer, Clyma, Dedrick, Clemmens and Replogle) prepared to go to the field.

A letter of introduction was sent to the WMIDD manager, requesting his approval of our proposed interviews with district personnel over a two or three-day period; approval was promptly granted. Background material on the district, and its legal, environmental, and historical context was assembled into a report and reviewed by the team (information collection step).

Issues thought to affect district performance were discussed, including the production, socio-economic, organization, economic, water control and environmental subsystems (development of work plans and method step). Hypotheses concerning district operations were formulated which could be proved or disproved with information from the field. Questions for interviews were formulated, although most were not finally used. It was found in the field that the more general questions tended to provide the most useful information. Beyond a few standard introductory questions, the interviews would usually proceed with initial answers suggesting subsequent questions.

The group travelled to the WMIDD and conducted approximately hour-long interviews with the district manager, chief engineer, watermaster, patrolman, head of the irrigation management service, dispatcher, ditchriders, farmers and farm irrigators (data collection step). Farmer contacts were made once the team was on site, to better accommodate changing schedules. The team was loosely split into two groups concentrating on district and on-farm operations. Interviews were usually conducted by one team member, with others present taking notes and suggesting overlooked or unclear areas for further questioning.

The team convened in private at half or whole day intervals, to monitor findings and progress. These interim meetings were very valuable for identifying areas of high and low performance in the district, and for reconsidering certain questions and interviewees. Some persons were interviewed more than once if these team discussions revealed missing or confusing information. Three days were spent in the field.

Once back at the lab, the team collated the interview results with existing information from the background report, the canal monitoring data, and internal documents given us by the WMIDD (analysis and synthesis step). Team members were asked to think deeply about what they had learned about operations in the WMIDD. Hypotheses developed earlier were rejected or accepted on the basis of the data collected and new understandings. It was found that as the field studies slipped further into the past, and as team members dealt with their everyday job duties, the analysis and synthesis phase became difficult to complete. The best insights into operations of the system studied came during periods when team members were isolated from distractions and engaged in intense discussion.

It was finally decided that analysis and synthesis should take the form of two team members making presentations on, respectively, the water delivery subsystem (Palmer) and on-farm water management subsystem (Dedrick), to the rest of the team. In both cases the most interesting results examined low performance resulting from poor or misapplied system management. In most cases the physical facilities were up to date and in good condition, but a lack of training by operators, and insufficient decision-making information cause low performance.

Since the main purpose of the rapid DA of the WMIDD was to provide the team training in the process, the final phase for this exercise was "exit" from the district, analogous to the report writing step in reconnaissance. The team decided to propose making a presentation of DA results to WMIDD management, but not to try to involve WMIDD in a grand program of management planning, unless asked by them to help organize such an effort. A presentation team consisting of Palmer, Clyma, Dedrick and Replogle met with the WMIDD chief engineer in February 1989 and outlined our understanding about high and low performance in district and on-farm operations, and the important factors contributing to performance.

The presentation was skeptically accepted by the chief engineer, though he had some strong disagreements. He did, however, suggest that the district needed a comprehensive improvement program and that the management planning - diagnostic analysis approach might be appropriate. At his request, an informal report of the presentation material was later sent to him, but the document was intercepted by the district manager. The manager became very upset by the implied criticism of district operations contained in the performance statements. Another presentation was eventually arranged, for the manager and his top officials. Face to face discussions during this presentation seemed to calm most of the anger, but something in our relationship with the district has probably been lost as a result of this snafu.

This episode points out another aspect of our DA exercise which could have been improved: that is, such a process and its results, conducted outside the auspices of the concerned organization, will almost always be seen as interfering and critical. The emphasis throughout should be on defining opportunities for improvement, and actually institutionalizing continuing

programs of improvement. Wherever possible, persons from the concerned organizations should be intensively involved in the management planning and DA processes.

Future Directions

Introduction to the application of management principles to irrigated agriculture has indicated that most of the poor performance of irrigation systems results from individuals' behavior due to low levels of training, conflicts of objectives between water users and water suppliers, and little effort spent on measurable evaluation of performance. Future research in canal systems operations should focus on the interactions between facilities and management policies and activities. Districts need better means to account for their water supplies and deliveries. Ditchriders need better guides for scheduling volume in their canals, for more accurately setting structures (when and how much), and for making better use of water measurement. Farmers and farm irrigators need better information about when and how to irrigate.

While much needed information has been at least tentatively identified through research, it is not being effectively transferred to the irrigation district and farm levels. While farmers have in principle the services of, for example, the SCS and extension offices (though even these seem to have failed the farmer who irrigates), water delivery agencies have no comparable organizations to draw on for technology transfer, cooperative research, or improvement planning. Research results have little value if they are not transferred to end users. Future research in canal systems would benefit greatly from involving irrigation districts in programs of action research, with proposed improvements actually tried out on trial bases, evaluated for effectiveness, and reconsidered for greater effectiveness.

In 1989, the CARIMA model will be installed, tested and calibrated to mimic the operations of the WM17.0 and M42.9 laterals which were monitored in the WMIDD. New management and regulation techniques will eventually be tested with the model, which will also be used to evaluate structure settings' effects on responsiveness and sensitivity. Several publications are scheduled, including papers on the process and results of the rapid DA of the WMIDD, irrigation structure responsiveness and sensitivity, and the relations between ordered, delivered and measured quantities of water in the two monitored canals. Further cooperation with WMIDD and the Imperial Irrigation District, Imperial California, is anticipated.

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PERSONNEL:

J. D. Palmer, A. J. Clemmens, A. R. Dedrick, J. A. Replogle, W. Clyma, J. Padilla, R. Gerard, R. Strand, J. Anderson.

TITLE: GERMPLASM DEVELOPMENT AND DOMESTICATION OF CUPHEA AND OTHER NEW CROP SPECIES

SPC: 2.1.03.1.a CRIS Work Unit: 5344-21000-001

INTRODUCTION

Numerous studies have demonstrated the need for and potential of research to create and develop new or alternative crops. Development of new crops with lower or more efficient water usage would serve an important role in the conservation of water in the arid and semiarid areas of the United States and other areas throughout the world.

For several years, this country's economy has suffered from an unfavorable balance of trade and payment. Importation of raw materials utilized by the U.S. oleochemical and other industries significantly add to this problem. The primary source of lauric acid and other medium-chain fatty acids utilized for manufacture of soaps and detergents, lubricants and other related products is imported coconut and palm kernel oils. The U.S. is also heavily dependent upon imported castor oil for its major supply of hydroxy fatty acids, a strategic material used in the production of lubricants, plasticizers, protective coatings, surfactants, and pharmaceuticals. Oils from seeds of Cuphea and Lesquerella species are prime candidates for domestic production of lauric acid and other medium chain fatty acids, and for hydroxy fatty acids, respectively.

PROCEDURE

Most species of cuphea are not adapted to the high temperatures experienced during the growing season in central Arizona. Failure to set seed is the major constraint, but good plant growth, development, and seed set can be obtained in greenhouses throughout the year. The major trust of research on cuphea at this location is to develop enhanced germplasm to be evaluated and used at other locations, chiefly Oregon, Iowa, and Georgia. Our germplasm development efforts are primarily concentrated on development of new genetic combinations through intra- and interspecific hybridization. The primary objective is to obtain new germplasm that will be useful in cultivar development for production in more temperate growing areas.

In contrast to cuphea, lesquerella is native to arid and semiarid areas, and has high potential for domestication and production in the arid Southwest. Research on lesquerella involves the development of improved germplasm utilizing conventional plant breeding, selection, and genetic methods. Cooperative research on determining water use requirements and the development of suitable cultural methods for lesquerella seed production are in progress with other scientists in the Arid Zone Crop Production Research Unit of the U.S. Water Conservation Laboratory.

RESULTS AND DISCUSSION

Cuphea:

The fertile amphidiploid (#1006) of C. leptopoda x C. laminuligera was evaluated for yield and growth characteristics in field plots at Corvallis, Oregon, during the 1988 growing season. The growth habit, seed set, and large seed size were judged to be very favorable in comparison with other cuphea species. However, harvested seed yields were disappointingly low as was that of essentially all other species tested. Seed shattering in the hybrid as well as with all other species continues to be a severe constraint to full commercialization of cuphea as a new domestic source of medium-chain fatty acids.

Four new interspecific hybrids of cuphea have been successfully completed (Table 1). One of the most interesting is the two crosses involving C. lanceolata x C. viscosissima, which produced fertile F_1 plants. C.lanceolata is a large plant with large sized flowers that is native to Mexico, and is highly cross pollinated. C. viscosissima is a small sized plant with small flowers that are highly self pollinated, and is unique in being the only species native to the U.S. The limited number of accessions of this species has been increased recently by the collection efforts of Dr. W. W. Roath in the central part of the country. The F_1 plant sets abundant seed in the greenhouse by self pollination. When this was recognized, vegetative stem tip cuttings were sent to Oregon, which were rooted and planted in the field to obtain F_2 seed during the 1988 growing season. The F_2 population, which should segregate widely, will be grown in Oregon in 1989.

The new cross involving C. viscosissima x C. lutea is of interest since it is only the second cross between species varying in predominant fatty acid production. The F_1 plants are sterile and are more vegetatively vigorous than either parent. However, the floral and other morphological characteristics of the F_1 tend to be intermediate relative to those of the parental species. Attempts are being made to restore fertility to the F_1 by creating an amphidiploid through the use of colchicine treatments to double the chromosome number.

The F_1 (#1070) of C. ignea x C. angustifolia is of special interest since it is the first interspecific hybrid between species within different taxonomic sections of the genus, Sect. Melvillia and Sect. Heterodon, respectively. The hybrid, which is sterile and can be propagated easily by cuttings, has good potential as a new pot or bedding plant. The plant has considerable vigor, and resembles C. ignea in that it lacks glandular hairs and produces abundant, bicolored pink flowers. The flowers are unusual in that the two, medium sized dorsal petals are nearly white and the four ventral petals are pink. All other cuphea species so far observed with bicolor flowers have ventral petals with a lighter color than their dorsal petals. Steps are being taken to restore fertility to the hybrid with treatments of colchicine to produce a fertile amphidiploid. Several research workers, plant growers, and propagators have expressed interest in testing some of these new hybrids for their

possible usage as new floral and bedding plants. Steps will be taken in 1989 to make an official germplasm release of several hybrids so that interested research workers and industry members may evaluate and utilize the germplasm.

Isozyme analyses of parental cuphea species and interspecific hybrids have been initiated. Isozyme band patterns of several parental species have been characterized and have been used to assay and confirm hybridity of several interspecific hybrids. A manuscript on this research has been prepared and submitted for publication. Three of five hybrids (C. lanceolata x C. viscosissima, C. viscosissima x C. lutea, and C. ignea x C. augustifolia) produced clear hybrid isozyme band patterns in at least one enzyme system (Fig. 1). The other two hybrids (C. llavea x C. procumbens and C. leptopoda x C. laminuligera) showed no clear hybrid band patterns in any tested enzyme system. It was concluded that utilization of this technique would be useful to identify hybrid plants in the seedling stage several months before floral and other morphological identification, and cytological verification could be effectively employed.

Lesquerella:

The 1987-88 planting of lesquerella was quite successful. Plantings were made at the Maricopa Agricultural Center on a level soil surface. Irrigation water was initially applied with sprinklers to encourage good, even seed germination, seedling emergence, and plant establishment. In addition to the breeding plots containing half-sib progeny families from 330 single plant selections, a replicated water use experiment, and a replicated plant population-planting method experiment were established.

After visual observation, 60 of the best lines among the 330 half-sib families were selected. Duplicate plots of these 60 lines were harvested for seed yield, and samples of the seeds were sent to the USDA/ARS Northern Regional Research Center for oil and lesquerolic acid analysis. Twenty three of the 60 lines were judged to have good combinations of seed yield and other agronomic plant characteristics. A total of 6 or 10% of the 60 tested progeny lines gave seed yields in excess of 1,800 kg/ha and oil yields of over 420 kg/ha and lesquerolic acid yields of over 225 kg/ha (Table 2). In Table 2 the performance of these 6 best lines are compared to that of the 10 best lines in 1985-86. Care must be exercised in making a direct comparison since the data were collected in two different years. However, it is reasonable to conclude that significant progress has been made after only one cycle of selection for increased seed, seed oil and lesquerolic acid yields.

The six best lines were planted in small, isolated, screen-caged plots on 11 October 1988 at the U.S. Water Conservation Laboratory in Phoenix to increase the seed of each by interpollination with honey bees. In addition, the six lines were planted together in a randomized complete block design with four replication in isolation in a large screened cage. Crossing among the six lines is being facilitated by honey bees. This will provide a measure of combining ability of each line, and will also

will provide a measure of combining ability of each line, and will also serve as a new elite base population from which further selection can be effected. In addition, seed of the 23 best lines were planted in the field in a randomized complete block design with eight replications in an isolated border at Maricopa to provide a new base population for further selection.

The lesquerella breeding populations were surveyed for isozyme patterns. Good resolution for lesquerella isozymes have been obtained using recipes provided by Dr. Diane L. Marshall of the University of New Mexico, Albuquerque, NM. The most useful gel and electrode buffers were the histidine-citrate (pH 6.0) system. The extraction buffer was a tris-HCl(pH 8.0) buffer with dithiothreitol added. Results of this preliminary research are summarized in Table 3. An experiment has been set up in the 1988-89 field planting at Maricopa within the breeding population to determine the mating system of lesquerella by using isozyme genetic markers. This research is being conducted cooperatively with Dr. Steven J. Knapp of Oregon State University, Corvallis, OR.

Quantities of seed have been distributed to cooperators for evaluation in Alabama, Arkansas, Colorado, Georgia, Illinois, Iowa, Minnesota, Missouri, and Oregon. Requests for trial amounts of seed have been received and filled from Australia, India, The Netherlands, Paraguay, and West Germany.

A total of $11,200 and $6,000 were transferred to the USWCL from the USDA/CSRS/SPPS Office of Critical Materials in FY 88 and FY 89, respectively. These funds are being utilized to provide support for an effort to conduct as assessment of the commercialization status of lesquerella as a new industrial crop source of hydroxy fatty acids. Also, the funds have been very helpful in supporting the breeding and agronomic research activities on lesquerella at the USWCL. The task force is chaired by Dr. Joseph Roetheli of the Office of Critical Materials and also involves Dr. Robert Kleiman and Dr. Kenneth Carlson of USDA/ARS Northern Regional Research Center, Peoria, IL, Dr. Melvin Blase and Mrs. Julia Goodell, University of Missouri, Columbia, MO, and Dr. A. E. Thompson of the USWCL in Phoenix. A report of the task force is expected to be completed and published the latter part of 1989.

An experimental crushing of part of the 1000 pounds of lesquerella seed, which was harvested by combine in 1988 and is currently stored at the USWCL seed storage facility, is anticipated in 1989. This will provide pilot plant information on both prepress and solvent extraction of oil, and provide oil for experimentation on grease formulations and other potential uses by USDA/ARS in Peoria, IL and by interested industry cooperators. It will also provide seed meal for preliminary animal feeding trials.

<u>Vernonia</u>

Seeds of 15 new accessions of <u>Vernonia galamensis</u> were received from Dr. R. E. Perdue, USDA/ARS Beltsville, MD. These represent several different subspecies and botanical varieties that had been collected by Dr. Perdue

Seeds of these accessions plus seed of the original accession from Ethiopia, which had been previously received and evaluated, were germinated and plants were grown in the greenhouse for transplanting into plots at Yuma and the USWCL early in 1989.

A request has been received from the USDA/ARS/National Program Staff to specifically include vernonia in the CRIS Project due to be revised in 1989.

General

Lack of adequate greenhouse space has been a severe constraint and has significantly hampered the germplasm enhancement efforts at this location. The four small 14 x 20' greenhouses at the USWCL were completely renovated and put into good operating condition with the use of R&M funds.

Efforts to purchase and construct a 30 x 72' quonset style plastic greenhouse were thwarted near the end of FY 88 when the single bid received was about three times higher than that expected. Since the start of FY 89 in October, 1988, purchase of all the essential elements for erection of a comparable 30 x 72' plastic greenhouse has been completed. Erection of the greenhouse is in progress and is expected to be operational by July, 1989. This badly needed space will greatly enhance the productivity of the new crops breeding and genetics effort.

SUMMARY AND CONCLUSIONS

Widely divergent species of cuphea have been successfully hybridized without resorting to embryo rescue techniques. Surprisingly, two hybrid combinations where the parental species shared the same chromosome number have proved to be highly fertile. This situation provides an opportunity for genetic segregation following recombination. The possibility exists that genetic recombinants for major factors currently constraining full commercialization can be found within the segregating F_2 populations. An F_2 population of C. lanceolata x C. viscosissima from seed produced in Oregon and in our greenhouse will provide this opportunity during the 1989 growing season in Oregon. Selection of mechanisms that will prevent or minimize seed loss by shattering is highly essential if cuphea production is ever to be successfully commercialized. Other interspecific hybrids of cuphea that have proved to be sterile are being treated with colchicine to produce fertile amphidiploids. This effort will now be able to proceed at a much more rapid pace with the provision of adequate greenhouse space.

The assessment of the commercialization status for lesquerella production is proceeding, and the effort appears to be generating positive results. The seed yields from agronomic experiments and that arising from the minimal breeding and selection effort are very promising. Seed yields of lesquerella should not be a constraint to commercial production. Preliminary conclusions of the assessment study point to the need for at least a 2 SY effort with about $300,000 annual support to conduct the necessary breeding and agronomic research in Arizona, and the oil extraction and utilization research at the Northern Regional Research

Center at Peoria, IL. Close involvement of industry in the process is being sought since it is highly essential for full commercialization.

PERSONNEL

A. E. Thompson, D. A. Dierig, D. H. Ronis, and E. R. Johnson

R. Kleiman and K. D. Carlson, USDA/ARS, NRRC, Peoria, IL, cooperating;
D. T. Ray, Plant Sciences Department, University of Arizona, Tucson, AZ, and
S. J. Knapp, Crop Science Department, Oregon State University, Corvallis, OR, cooperating.

Table 1. Summary of New Successful Interspecific Hybrids of _Cuphea_.

	Female Parent				Male Parent					
Cross Number	Species	Acc. No.	Chrom-osome No.	Predom-inant Fatty Acid	Species	Acc. No.	Chrom-osome No.	Predom-inant Fatty Acid	No. of Hybrid Plants	Comments
1067	C.lanceolatata	(A226)	6	C10:0	C.viscosissima	(A49)	6	C10:0	100	Fertile hybrid with F_1's producing abundant F_2 seed.
1068	C.lanceolata	(A252)	6	C10:0	C.viscosissima	(A49)	6	C10:0	22	Fertile hybrid with F_1's producing abundant F_2 seed.
1069	C.viscosissima	(A49)	6	C10:0	C.lutea	(A381)	14	C12:0	13	Sterile, second successful hybrid between fatty acid groups.
1070	C.ignea	(A57)	15	C10:0	C.angustifolia	(A5)	12	C10:0	5	Sterile, first successful hybrid between species in different taxonomic sections of genus (_C. ignea_ - Sect. Melvilla, _C. angustifolia_ - Sect. Heterodon).

Table 2. Improvement in Yield Performance of Lesquerella fendleri Progenies of Best Single Plant Selections Tested in 1985-86 and 1987-88 Cropping Seasons.

Yield Parameters	1985-86 10 Best Families Range Low	High	Mean (x̄)	1987-88 6 Best Families Range Low	High	Mean (x̄)	Percentage Change in Mean From 1985-86 To 1987-88
Plant Population (million/ha)	.170	.903	.481	.537	1.560	.920	+91
Plant Dry Weight (kg/ha)	7,233	11,172	9,341	9,754	19,289	12,868	+38
Plant Height (cm)	31.3	39.2	35.6	34.5	55.0	41.4	+16
Harvest Index (%)	13.9	23.4	17.1	13.5	18.5	16.2	- 5
1000 Seed Weight (g)	.542	.726	.621	.514	.620	.558	-10
Seed Yield (kg/ha)	1,390	1,740	1,573	1,804	2,610	2,042	+30
Oil Content (%)	19.10	25.70	22.61	22.60	28.75	26.08	+15
Lesquerolic Acid Content (%)	52.00	54.60	53.32	51.05	53.35	52.30	- 2
Oil Yield (kg/ha)	279	445	357	421	667	533	+49
Lesquerolic Acid Yield (kg/ha)	149	238	190	225	350	278	+46

Table 3. Survey of Isozyme Patterns Within a Breeding Population of Lesquerella fendleri.

Enzyme	Genetic Loci Identified (No.)	Genetic Loci Segregating (No.)	Protein Structure
6-Pgd	1	1	Dimer
Pgm	4	2	Monomer
Idh	1	1	Dimer
Pgi[a]	2	2	Dimer ?
Dia[a]	2	1	?
Fest	1	1	Monomer
Aco	1	1	Monomer

[a] Unclear inheritance.

Fig. 1 Band patterns of (A) Pgm isozymes of C. viscosissima x C. lutea, (B) 6-Pgd isozymes of C. ignea x C. angustifolia, and (C) Pgm isozymes of C. lanceolata x C. viscosissima. Lanes 1- 4 are from the female parent, lanes 5-8 are from the interspecific hybrid, and lanes 9-12 are from the male parent.

TITLE: ISOZYME TECHNIQUES FOR NEW CROPS

SPC: 2.1.03.1.a CRIS Work Unit: 5344-21000-001
2.1.03.1.b 5344-13210-001

INTRODUCTION

The usefulness of gene markers for plant breeding and genetic studies is well established. For new crops development, gene markers are of vital importance since so little is known about the genetics of these plant species. Gene markers can be of immense value not only in understanding the genetics of the plant species but also in increasing the efficiency of the breeding effort. Some of the more practical applications include confirming hybridity in crosses, fingerprinting lines and species, speeding up backcrossing and introgression of traits between species, and indirect selection via linked quantitative traits.

Electrophoretic procedures, in particular starch gel isozyme analysis, has been used to assay genetic enzyme variants found in wild relatives and breeding populations of new crops species. Once variants were detected, crosses or self-pollinations can be made in order to conduct further genetic studies, especially inheritance and linkage studies.

PROCEDURE

For isozyme analysis of new crop species, a 13% starch gel was used. Run time was generally four hours using a constant voltage of 250V. For all species analyzed, seedling leaf tissue gave the best resolution. All isozyme procedures followed the methodology of Cardy and Beversdorf (1984) except for sample preparation of leaf tissue. Leaf samples were placed in wells in chilled porcelain plates and ground with a test tube in 2 drops of extraction buffer.

For *Cuphea* species, the 'AC' buffer system (Clayton and Tretiak, 1972) worked well for the enzymes Pgm, 6-Pgd, Aco, Skdh, Dia, and Pgi. The #2 buffer system (Soltis et al, 1983) gave good resolution for the enzymes Pgm, Aco, Pgi, Dia, Me, Idh, and Adh. The extraction buffer was from Wendel and Parks (1982).

For *Parthenium* species the 'B' buffer system (Cardy and Beversdorf, 1984)) gave good resolution for Mdh, 6-Pgd, Skdh, Pgi, Pgm, and Aco. The #2 buffer system (Soltis et al, 1983) also worked well for Skdh, Aco, Me, and Pgm. The extraction buffer used was from Wendel and Parks (1982).

For *Lesquerella fendleri*, the 'B' buffer system (Cardy and Beversdorf, 1984) worked well for the enzymes Idh, Dia, Pgm, Fle, and 6-Pgd. The extraction buffer was a 0.1M tris HCL (pH 8.0) with 3g/L DTT.

RESULTS AND DISCUSSION

Cuphea

Twelve species, including interspecific hybrids, were surveyed for isozyme patterns. The enzymes Pgi, Pgm, Skdh, Mdh, 6-Pgd, Dia, Idh, Me, Adh, and rubisco stained well for most species. Aco stained clearly only in seedling or pollen tissue. There were sufficient isozyme differences for distinguishing (fingerprinting) species. Cross-pollinating species (*C. lanceolata, C. leptopoda, C. laminuligera, C. llavea*) had substantial within-species and within-accession genetic variation. Self-pollinating species (*C. viscosissima, C. lutea*) showed high within-species genetic uniformity. A comparison of parental plants with interspecific hybrids confirmed hybridity for *C. lanceolata* x *C. viscosissima*, *C. viscosissima* x *C. lutea*, and *C. ignea* x *C. angustifolia* (paper in review). F_1 plants of the fertile hybrid *C. lanceolata* x *C. viscosissima* were selfed to produce an F_2 population for further genetic studies including inheritance and linkage, and mapping quantitative traits. A rubisco variant, detected among the twelve species, may be useful for determining evolutionary relationships among the species.

Parthenium

Four species plus many lines of guayule were surveyed for isozyme patterns. The enzymes Aco, Pgm, Pgi, Pgd, Me, and Dia gave the best staining results. Isozyme differences were great enough to allow fingerprinting of species. Considerable variation was also detected within guayule lines for Aco, Pgm, and Skdh and among a set of purported diploid plants for Pgi band patterns. Crosses were made between guayule plants with different banding patterns for inheritance studies. Three rubisco variants were detected among four *Parthenium* species and maternal inheritance of rubisco was established in interspecific crosses of *P. argentatum* x *P. tomentosum*. A chloroplast Pgi locus was detected by its absence in pollen samples.

Lesquerella

Lesquerella fendleri breeding populations were surveyed to determine which enzymes stained well and showed variation for isozyme band patterns. Idh, 6-Pgd, Pgm, and fluorescent esterase showed variation among and within the breeding populations. The data will be used to conduct a mating study in a field population of lesquerella. A selfing program was also initiated for an inheritance and linkage study of isozyme loci.

SUMMARY

Considerable progress has been made in establishing isozyme procedures for genetic studies of *Cuphea*, *Parthenium*, and *Lesquerella*. Substantial variability was detected within and among cuphea species. Banding patterns were used to confirm hybridity among three interspecific crosses of cuphea. There were sufficient isozyme differences to distinguish parthenium species. Isozyme variation was also detected among guayule lines and some variation was detected within lines. For *Lesquerella*, four enzymes showed potential isozyme loci among *L. fendleri* breeding lines. Rubisco variants were detected among *Cuphea* and *Parthenium* species with

the latter variants showing maternal inheritance. For all three new crops, isozyme inheritance studies were initiated to establish genetic loci in preparation for further genetic and breeding studies.

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PERSONNEL

D. H. Ronis, D. A. Dierig, A. E. Thompson, and E. R. Johnson

APPENDIX

LIST OF 1988 PUBLICATIONS
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ALEXANDER, W. L. BUCKS, D. A. and BACKHAUS, R. A. 1988 Irrigation water management for guar seed production Agron. Journal. 80(3):447-453. (published) (ms#1267)

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